GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[x] ORIGINAL
[ ] REVISION NO. ____

Project No. E-16-604 (follow on to E-16-646) DATE: 6/24/81

Project Director: Dr. Ben T. Zinn School/Lab Aerospace Engineering

Sponsor: Department of Energy, Oak Ridge, TN

Type Agreement: Contract # DE-AS05-79ER/0068, Mod #2

Award Period: From 10/1/80 To 11/30/81 (Performance) ____ (Reports)

Sponsor Amount: $100,000 (mod # 2 only) Contracted through:

Cost Sharing: $6,827 (E-16-354) GTRI/~~GIT~~

Title: Development of a Coal Burning Pulsating Combuster for Power Generation

ADMINISTRATIVE DATA OCA CONTACT Leamon R. Scott

1) Sponsor Technical Contact: A. H. Frost, Jr., Chief; Contract Mgmt. Branch, Procurement & Contracts Div; Dept. of Energy; P.O.Box E; Oak Ridge, TN 37830 Phone 615/576/0791

2) Sponsor Admin./Contractual Contact: Walker Love, Contracting Officer; Dept. of Energy; Office of Research Operations; P.O. Box E; Oak Ridge, TN 37830 phone 615-576-7564

Reports: See Deliverable Schedule Security Classification: N/A

Defense Priority Rating: N/A

RESTRICTIONS

See Attached government contract Supplemental Information Sheet for Additional Requiremen

Travel: Foreign travel must have prior approval - Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with GIT (contract article B-XII)

COMMENTS:

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GEORGIA INSTITUTE OF TECHNOLOGY | OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION SHEET

Date 6/22/82

Project Title: Development of a Coal Burning Pulsating Combuster for Power Generation

Project No: E-16-604

Project Director: B.T. Zinn

Sponsor: Department of Energy, Oak Ridge, TN

Effective Termination Date: 11/31/81

Clearance of Accounting Charges: 11/31/81

Grant/Contract Closeout Actions Remaining:

- [ ] Final Invoice and Closing Documents
- [x] Final Fiscal Report
- [x] Final Report of Inventions
- [x] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other ______

Assigned to: Aerospace Engineering (School/~~Laboratory~~)

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FORM OCA 10:781

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November 6, 1980

Dr. Ernest Blase
Department of Energy
Washington, D.C. 20585

Subject: Progress report for the period October 1 through October 31, 1980 for work conducted under contract DE-A505-79-ER-10068

During this reporting period a review of existing approaches for the computation of combustion efficiences in other combustion systems has been performed. Basically, two different procedures are employed; namely, a gas analysis of the exhaust products coupled with chemical analysis of the solid residues and soot - and the temperature method. The first method permits, in the case of coal burning, the calculation of combustion losses by the determination of the percentage of carbon monoxide in the gaseous products of combustion as well as the percentage of unreacted carbon in the solid residues and soot. The temperature method on the other hand determines the combustion losses by comparing the actual temperature and the ideal (i.e., for complete combustion) theoretical exhaust gas temperature at the combustor exit. In this connection it should be pointed out that the temperature method also requires the determination of heat losses through the combustor walls up to the position where temperatures are compared.

Based upon experience to date with the developed pulsating combustor, it appears that the efficiency of the developed pulsating combustor could be best determined by evaluating the combustion losses. The latter will be determined from measurements of the composition of the exhaust products. To improve this measurement, an effort is currently underway to determine the possibility of indirect measurement of the percentage of carbon in the solid residues and soot by using only gas analysis, velocity measurements and continuity equations.

Experimental efforts conducted during the report period were concerned with the alleviation of problems that arise as a result of the accumulation of ash and partially burned coal particles at the bottom of the combustion bed. This accumulation of burned material at the bottom of the bed eventually results in substantial blockage of the oxidizer flow passages and the cessation of pulsations. Efforts directed at the alleviation of this problem involved the evaluation of the effectiveness of different coal bed basket designs and the consideration of utilizing "active" combustion beds that would utilize some sort of a mechanical stirrer to periodically mix the contents of the bed and thus prevent the clogging of oxidizer flow passages.

In another activity undertaken during the reporting period a series of tests was performed to check the repeatability of the data measured for the same experimental configuration. These tests have shown that reproducible data can be obtained in the developed facility.

In the next reporting period, efforts directed at the determination of the pulsating combustor efficiency will continue. Furthermore, an activity aimed at the determination of potential application of pulsating combustor will be initiated.

Sincerely,

Ben T. Zinn

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December 9, 1980

Dr. Ernest Blase
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Subject: Progress report for the period November 1 through November 30, 1980 for work conducted under contract DE-A505-79-ER-10068.

In experiments conducted to date, the combustion of the coal in the bed had resulted in the buildup of a layer of ash and unburned coal in the bottom of the bed some time after initiation of burning. This accumulation of material at the bottom of the bed results in blockage of air flow and the cessation of pulsations. During the reporting period, tests with different coals were performed and the problem was practically eliminated when low ash content coals were burned. It has also been found that as the percentage ash in the coal increases, the blockage problem can be eliminated by increasing the openings in the bottom grid of the combustion bed. This, in turn, results in a larger fraction of ash and unburned coal. To avoid the losses of unburned coal, the recirculation of the falling unburned particles through the bed will be considered in the near future.

During the reporting period the metal wire basket that holds the burning coal bed was redesigned to prevent the accumulation of ash and unburned coal at the bottom of the bed, as discussed above. This redesigned basket was then used in a series of tests that were designed to investigate the effect of cooling the combustion flow at the 3L/4 location upon the operation of the combustor. Theoretical consideration of the indicated cooling process and communications with Dr. Severyanin in the USSR indicate that such a cooling process should enhance the pulsations in the tube. The effect of cooling of the hot gases at the 3L/4 location was investigated by flowing .5 gal/min of water through a copper coil placed at the indicated location. The temperature difference between the inflowing water and the outflowing water was of the order of 40°F. Although the heating of the water resulted in an increase in the amplitude of oscillations by 2dB, no change in the coal burn rate has been observed. This matter will be further investigated in the future.

Since the tests performed during this period determined a final configuration for the basket carrying the coal burning bed, the group is considering the acquisition of a Beckman Model 865 non-dispersive infrared analyzer for measurement of carbon monoxide and carbon dioxide concentration at the combustor exhaust. This instrument is designed for applications where it is desired to continuously monitor a particular component in a gaseous stream. These gas concentration measurements are directly related to the evaluation of combustion losses occurring in the process of burning, which will lead to the determination of the combustor efficiency.

In the last monthly report it has been stated that the analytical investigation of possible methods for the measurement of the combustion efficiency in the developed pulsating combustor have been completed. The practicality of the possible efficiency measurement techniques have been investigated during the last reporting period. As part of this effort, possible methods and available instruments for the measurement of CO and CO_2 concentrations are under consideration. Once the optimum method(s) for the measurement of these concentrations is developed, steps will be taken to develop the needed measurement capabilities that will allow for the determination of the combustor efficiency.

During the next report period, efforts will continue on the development of capability for measuring the combustion efficiency.

Also some efforts will be devoted to a theoretical investigation of the effects of NO_x formation upon the determination of the combustor efficiency.

Sincerely,

Ben T. Zinn
Principal Investigator

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Ben T. Zinn
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January 7, 1981

Dr. Ernest Blase
Department of Energy
Washington, D.C. 20585

Subject: Progress report for the period December 1 through December 31, 1980 for work conducted under contract DE-A505-79-ER-10068.

During this reporting period, work was done on the development of methods for measuring carbon monoxide and carbon dioxide concentrations in the flow stream at the combustor's exhaust. These measurements are directly related to the evaluation of the combustion losses and, consequently, to the evaluation of the pulsating combustor's efficiency. Also, a theoretical investigation aimed at the reduction of the number of measurements needed for the combustor efficiency determination was undertaken.

Some efforts have been devoted to the investigation of the effects of NO_x and SO_x formation on the calculation of the combustor efficiency. The conclusion was reached that the presence of these gases can be ignored as far as the evaluation of combustion losses for coal burning is concerned.

Experimental work conducted during this period was concerned with the determination of the optimum range of coal sizes that would allow for continuous, high burn rate operation of the pulsating combustor. It has been found that for low ash content coals, the combustor's performance is improved when coal particle sizes are in the range of 1/2 inch to 1 inch. The size of the coal particles was determined by passing the coal through a set of different mesh size sieves.

An investigation of the possibility of burning wood in the Rijke Combustor was also initiated during the reporting period. Initial results were most encouraging as extremely high wood combustion rates were observed. Furthermore, the wood appeared to burn cleanly leaving little refuse behind.

Finally, an investigation has been undertaken to determine potential applications of the pulsating combustion process in industry. Application currently under consideration include steam raising and drying for the lumber, paper and lumber industries.

Dr. Ernest Blase
January 7, 1981
Page 2

Efforts under this contract during the next reporting period will concentrate on the determination of the efficiency of the combustor, attempts to control the fuel/air ratio and the investigation of potential applications of pulsating combustors.

Sincerely,

Ben T. Zinn

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February 10, 1981

Dr. Ernest Blase
Department of Energy
Washington, D.C. 20585

Subject: Progress report for the period January 1 through January 31, 1981 for work conducted under contract DE-A505-79-ER-10068.

Efforts conducted during this reporting period concentrated on the search for a method for controlling the air/fuel ratio in the pulsating combustor. This effort has been undertaken because of available evidence showing that the developed combustor operates under fuel lean conditions and indications from the Russian literature that the efficiency of the combustor may depend upon the fuel/air ratio.

The first series of tests involved the placement of a perforated disk at different heights within the combustor in an attempt to control the flow rate of the air through the combustor. The results of these tests showed that, as expected, the insertion of the disk has a strong effect upon the acoustics of the system. Furthermore, the addition of the disk resulted in heavier smoke production, lower amplitude and lower burn rates, thus resulting in inferior combustor performance.

Since the flow rate of air is partially controlled by buoyancy effects, a number of attempts to control the flow rate of the air by changing the length of the combustor were conducted. Reducing the length of the combustor from its current value of 108 inches was expected to reduce both the chimney effect and the air flow rate through the combustor and increase the frequency of pulsations. These series of tests has shown that the combustor performance deteriorates with length decrease and that pulsating combustion stops when the combustor length reduces to 60 inches. Considering the results of this series of tests and the physics of the problem, it appears that the combustor performance might improve by increasing its length. The correctness of this conjecture will be investigated during the next reporting period.

Work is also currently underway on the addition of acoustic decouplers at both ends of the combustor that will provide means for controlling the air flow rate through the combustor without affecting the combustor's acoustics. This work will continue during the next reporting period.

Since the amount of air flowing through the combustor appears to be a very important parameter in the determination of the combustion efficiency, work on the development of capabilities for accurately measuring the combustor's flow velocity continued during the reporting period. Air flow is currently being measured by means of a TSI hot film transducer coupled to a DISA anemometer unit. Both the probes and the anemometer unit were recalibrated in the Georgia Tech Aerospace Engineering low turbulence wind tunnel and their results checked very well - within 2% - with the data output given by Pitot tube measurements.

Finally, some efforts were expended on an error analysis of the accuracy of the previously derived approach for the determination of the combustor efficiency.

In addition to those mentioned above, the investigation of the combustor's combustion efficiency and efforts to control the combustor's air/fuel ratio will continue during the next reporting period.

Sincerely,

Ben T. Zinn

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March 11, 1981

Dr. Ernest Blase
Department of Energy
Washington, D. C. 20585

Subject: Progress report for the period February 1 through February 28, 1981 for work conducted under Contract DE-A505-79-ER-10068.

During this reporting period, some of the experimental work concentrated on the investigation of the possibility of controlling the fuel/air ratio of the combustion process by means of an acoustic decoupler attached to the bottom of the combustor. The acoustic decoupler consisted of a drum having a diameter and length 4 and 6 times larger than the combustor's diameter, respectively. As expected, the addition of the decoupler did not stop the pulsations and the combustor operated regularly with approximately the same frequency of oscillations. It appears that the air/fuel ratio under the self aspirating mode of operation could be controlled by changing the diameter of the opening for the air intake in the decoupler.

In another effort, a new series of experiments, designed to investigate the characteristics of the pulsating combustion operation under forced air flow conditions, was initiated. In this study, forced air flow was supplied to the combustor through a pipe that connected to the above-mentioned acoustic decoupler. A series of preliminary tests in which the air flow rate was varied was conducted and the results showed that the varying the air flow rate (and thus affecting the air/fuel ratio) affected the nature of the pulsation and the temperature of the generated combustion products. Pulsating combustion was obtained when burning under both fuel lean and fuel rich conditions and it appears that maximum output is obtained when operating at or near stoichiometric fuel/air ratio. The use of a forced air flow offers the possibility of controlling the operation of the combustor and these studies will continue in the future.

Work on the development of capabilities for air flow velocity measurements in the combustor continued during this period. The combustor was operated with a forced air flow whose volumetric flow rate was measured by a rotameter. Knowing the air properties and the combustor's cross sectional area, the measured flow rate could be used to determine the air velocity in the combustor. Simultaneously, the air flow velocity at the combustor's entrance was also measured by means of a TSI hot film transducer coupled to a DISA anemometer unit. The velocities measured with the hot film probe and the rotameter agreed for a non pulsating mode of the operation of the combustor and current efforts are concerned with the development of velocity measurement capabilities when the combustor is operating under pulsating conditions.

Additional efforts during the reporting period investigated potential applications of the pulsating combustion process, the purchase of CO and CO_2 analyzers that will be needed for combustion efficiency measurements and the design of a sampling train to be used for withdrawing gas samples from the combustor and feeding them to the analyzers. All of these efforts as well as the experiments with the forced flow pulsating combustor will continue during the next reporting period.

Sincerely,

Ben T. Zinn
Principal Investigator

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April 7, 1981

Dr. Ernest Blase
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Washington, D. C. 20585

Subject: Progress report for the period March 1 through March 31, 1981 for work conducted under Contract DE-A505-79-ER-10068

Part of the efforts conducted during the reporting period were concentrated on the improvement of the design of the sampling train to be used for feeding gas samples from the combustor to the CO and CO_2 infrared analyzers which will be needed for the determination of the efficiency of burning coal in the pulsating combustor. In addition, efforts were expanded on the development of an alternate method for measuring combustion efficiency that would utilize isokinetic sampling and chemical analysis of unburned particulate matter. Although this procedure will not provide combustion efficiency as a function of time, it will be used to check the results obtained with the gas analysis. Additional efforts during the last reporting period involved the pricing and purchase of some of the components that are needed for the above mentioned sampling trains.

Experimental work conducted during this period concentrated on the investigation of the burning of wet wood under forced flow oscillatory and non oscillatory conditions. In a series of tests wood chips containing different amounts of water were burned in the pulsating combustor. While this series of tests is not completed yet, results obtained to date show that wood containing up to 40% moisture can be burned under pulsating conditions. Tests with wood containing higher percentages of moisture and green wood will be conducted in the next reporting period. Another potential advantage observed in the above mentioned tests was the much faster burn rate of wood with the same moisture content under oscillatory conditions as compared to its burning under non oscillatory conditions.

During the next reporting period, work will proceed with the acquisition, fabrication and installation of the needed gas and particulate sampling trains. Efforts will also be expanded on developing a data reduction software for the infrared analyzers outputs that will be fed into a mini computer and then used in the determination of the time dependence of the combustion efficiency.

Sincerely,

Ben T. Zinn

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May 12, 1981

Dr. Ernest Blase
Department of Energy
Washington, D. C. 20585

Subject: Progress report for the period April 1 through April 30, 1981 for work conducted under Contract DE-A505-79-ER-10068.

Part of the efforts expended during this reporting period consisted of pricing and acquisition of components of the sampling line to be used for particulate collection in the products of combustion. Particulate analysis will provide an additional methdod of determining the system's combustion efficiency and will serve as a check for the results obtained by means of carbon monoxide and carbon dioxide concentration measurements.

Experimental work conducted during this reporting period concentrated on the investigation of the system's operation when a decoupling chamber is attached to its exhaust port. This chamber - 12 inches higher and 11 inches in diameter - will provide means for a more effective heat collection from the products of combustion, therefore increasing the system's thermal efficiency. These tests showed that the addition of the decoupling chamber did not affect the operation of the pulsating combustor.

Work is currently under way on the installation of a coil heat exchange inside the decoupling chamber. This heat exchanger will be used to heat water circulating through its coils. The heat transfered to the water will be measured and used to determine the thermal efficiency of the system. Future efforts will concentrate on the determination of the dependence of the system's thermal efficiency upon various system parameters.

During the next reporting period, the sampling train for carbon monoxide and carbon dioxide concentration measurements will be developed. These measurements will provide data for the computation of the combustion losses occurring in the system. Once installed, preliminary tests will be conducted to assure the proper operation of the system.

Sincerely,

Ben T. Zinn

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June 12, 1981

Mr. Harry Ritz
Mail Stop 920-208
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Subject: Progress report for the period May 1 through May 31, 1981 for work conducted under Contract DE-A 505-79-ER-10068.

Part of the work conducted during this reporting period consisted of the installation of the sampling lines to be used in the analysis of the gaseous and particulate combustion products. A control panel for holding the sampling system's flowmeters and control valves was designed and built. The completion of the installation of the sampling lines has been delayed by postponents in the delivery of some system components and it will be completed during the next reporting period.

Experimental work conducted during this period concentrated on the investigation of the distribution of the heat generated from wood burning under pulsating conditions. To minimize heat losses, the combustor was insulated with a 5 cm layer of fiber glass. Tests were conducted with 0.4 gallons/min of water flowing through a coil heat exchanger that was placed at the top of the pulsating combustion and wood was burned at a rate of 52,500 Btu/hour. This rate can be considerably increased once an automated wood feed system becomes available. In this connection it should be pointed out that a high energy release rate represents one of the advantages of the pulsating combustor as the indicated energy was released in a relatively small combustion bed, indicating a high combustion intensity. Energy balance considerations showed that the combustion was practically complete as most of the energy available in the wood could be accounted for. This matter will be checked again when the combustion efficiency of the pulsating combustion process will be investigated with the sampling lines. Another interesting observation made during the course of these experiments was the fact that the burning rate of wood when burning under pulsating conditions is approximately 50% higher than the corresponding steady state burning.

During the next reporting period, the installation of the sampling trains for particulate and gas analysis will be completed. These will be used to measure the carbon monoxide and carbon dioxide concentrations that will be used in the determination of the combustion losses occurring in the combustor.

Sincerely,

Ben T. Zinn

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July 9, 1981

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Subject: Progress report for the period June 1 through June 30, 1981 for work conducted under Contract DE-A 505-79-ER-10068.

Some of the efforts expanded during this reporting period consisted of completion of the installation of the sampling line to be used in the analysis of the gaseous products of combustion of the pulsating combustor. An ice bath and a separation system has been designed and built in order to extract water vapor from the gas sample to be fed into the recently acquired infrared analyzers. In addition, the installation of the sampling train for the particulate collection and analysis is nearing completion.

A series of tests was conducted during the reporting period utilizing wood as fuel to determine the dependence of the amplitude of the acoustic pressure upon the air/fuel ratio, the magnitude of the steady flow velocity and the presence of acoustic decouplers at both ends of the combustor. The results of these tests are summarized on the attached figure where x is the percentage moisture in the wood. These results show that maximum amplitude pulsations occur for stoichiometric or slightly fuel rich air/fuel ratios. These results also show that the magnitude of the amplitude of the oscillation increases when the magnitude of the steady air velocity increases. Finally, these results also show that the addition of the decouplers results in a pulsation amplitude reduction.

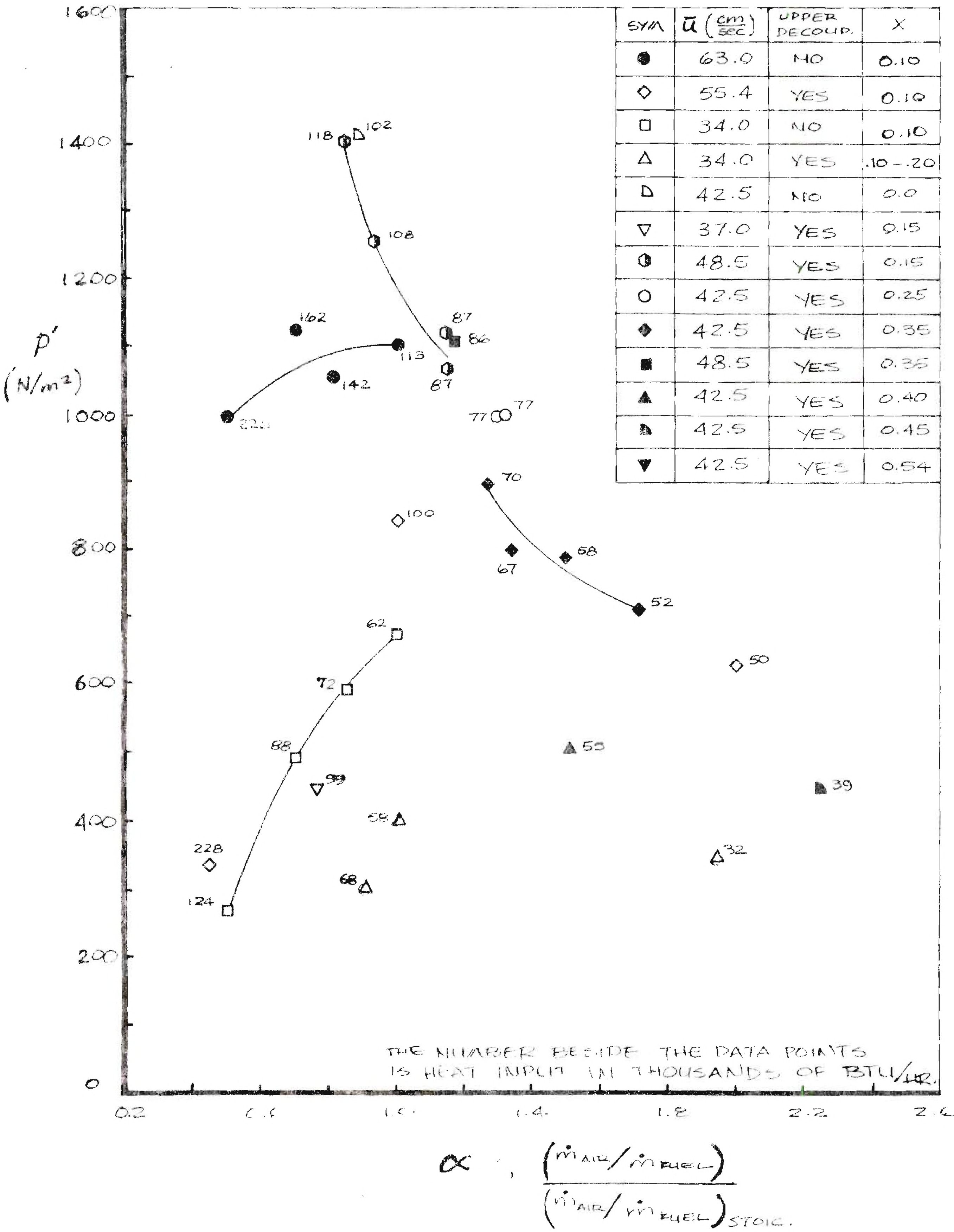
During this series of tests, the pressure in the air line was increased, allowing for a much higher feed rate of wood which provided a heat release rate of the order of 110,000 Btu/hour, a little more than twice of the heat release reported during the last reporting period. With a proper feed system for wood, it is believed that the heat release can be doubled again.

During the next reporting period, the installation of the particulate and gaseous products sampling trains will be completed and the recently purchased CO and CO_2 IR analyzers will be checked out and connected to the sampling trains. Initial tests will be conducted to check out the operation of the sampling lines and the measured CO and CO_2 concentrations will be used to compute the combustion losses occurring in the combustor.

Sincerely,

Ben T. Zinn

BTZ/jj



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● | 63.0 | NO | 0.10
◇ | 55.4 | YES | 0.10
□ | 34.0 | NO | 0.10
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D | 42.5 | NO | 0.0
▽ | 37.0 | YES | 0.15
◐ | 48.5 | YES | 0.15
○ | 42.5 | YES | 0.25
◆ | 42.5 | YES | 0.35
■ | 48.5 | YES | 0.35
▲ | 42.5 | YES | 0.40
◭ | 42.5 | YES | 0.45
▼ | 42.5 | YES | 0.54
p′ (N/m²)
0
200
400
600
800
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1.0
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August 11, 1981

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Subject: Progress report for the period July 1 through July 31, 1981 for work conducted under Contract DE-A 505-79-ER-10068.

During the last reporting period, efforts were expanded on the calibration of the non dispersive infrared analyzers for the measurement of carbon dioxide and carbon monoxide concentrations. These concentrations will be used in forthcoming tests in the determination of the combustion efficiency of the pulsating combustor when it's burning coal. The calibration of the zero point on the instrument's scale presents no problems since the recommended gas for this procedure is dry nitrogen. The up scale calibration requires, however, a special mixture of the gas being measured in nitrogen, with a concentration corresponding to approximately 90% of the full scale deflection with an as precise as possible composition analysis. After familiarization with the calibration procedure recommended by the instrument's manual, these mixtures were ordered and they are expected to arrive within the next few days.

In addition, the assembly of the train for particulate sampling and analysis has been completed. Slight modifications in the original train design were made in order to use the additional head of the dual-head pump being used in the gas analysis. This particulate sampling system is designed to collect more than 99.7% of the particles having diameters above 0.3 micron. The collected particulates will also be used to provide an additional, independent determination of the combustion efficiency of the pulsating combustor.

During the next reporting period, experiments will be conducted to determine exhaust gas concentrations. In addition, attempts will be made to determine the particulate concentration in the exhaust flow under isokenetic sampling conditions.

Sincerely,

Ben T. Zinn

BTZ/jj

LIBRARY DOES NOT HAVE

Progress Report - August 1 through August 31, 1981

E16 604

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October 12, 1981

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Subject: Progress report for the period September 1 through September 30, 1981 for work conducted under Contract DE-A 505-79-ER-10068.

During the last reporting period a data acquisition system to be used during testing with the pulsating combustor was developed. A schematic of this system is shown in Fig. 1. Specifically, this system utilizes a tape recorder to simultaneously record temperatures in different sections of the combustor, concentrations of carbon monoxide and carbon dioxide in the flue gas, amplitude of pressure oscillations and the feed rate of the coal. In addition, a rotameter capable of handling higher flow rates was installed in the air line that supplies air to the combustor in order to increase the air handling capacity of the system.

A series of tests whose objective was the quantitative determination of the combustion efficiencies of the pulsating combustor under different operating conditions was initiated. Specifically, the tests conducted during the reporting period investigated the dependence of the combustion efficiency upon the air/fuel ratio and incoming air mean velocity. The initial series of tests investigated the combustor performance for stoichiometric air/fuel ratios and different air velocities. Combustion efficiencies higher than 90% were measured for air mean velocities higher than 70 cm/sec. The feed rate during these experiments was about 75 gr/min, corresponding to approximately 750,000 Btu/hour per square foot of combustion bed. The performance of the combustor deteriorated, however, as the air velocity decreased below 70 cm/sec and, at 50 cm/sec, oscillatory operation became very difficult to achieve and the combustion efficiency decreased more than 15%. The coal used in these experiments had a heat value of 13,900 Btu/lb and an average size between 1/2" and 1/4".

Observations of the structure of the coal bed indicate that during pulsating operation the bed consists of four layers as shown in Fig. 2. Starting at the top, the bed consists of a layer of fresh coal followed by a layer of agglomerated coal, followed by a layer of smaller diameter coal, followed by a layer of ash particles that fall through the holes of the grid that supports the bed. During non pulsating operation, the burn rate decreases and the thickness of the agglomerated coal layer continually increases with time to the point that it practically occupies the whole bed, preventing a steady mode of operation. These characteristics of the bed are probably responsible for the lower values of combustion efficiencies observed during non oscillatory burning.

The series of tests described in this letter will continue during the next reporting periods. They will concentrate on the determination of the pulsating combustor performance at different air/fuel ratios, different coal feed rates, different air velocities, and different coal sizes.

Sincerely,

Ben T. Zinn

BTZ/jj

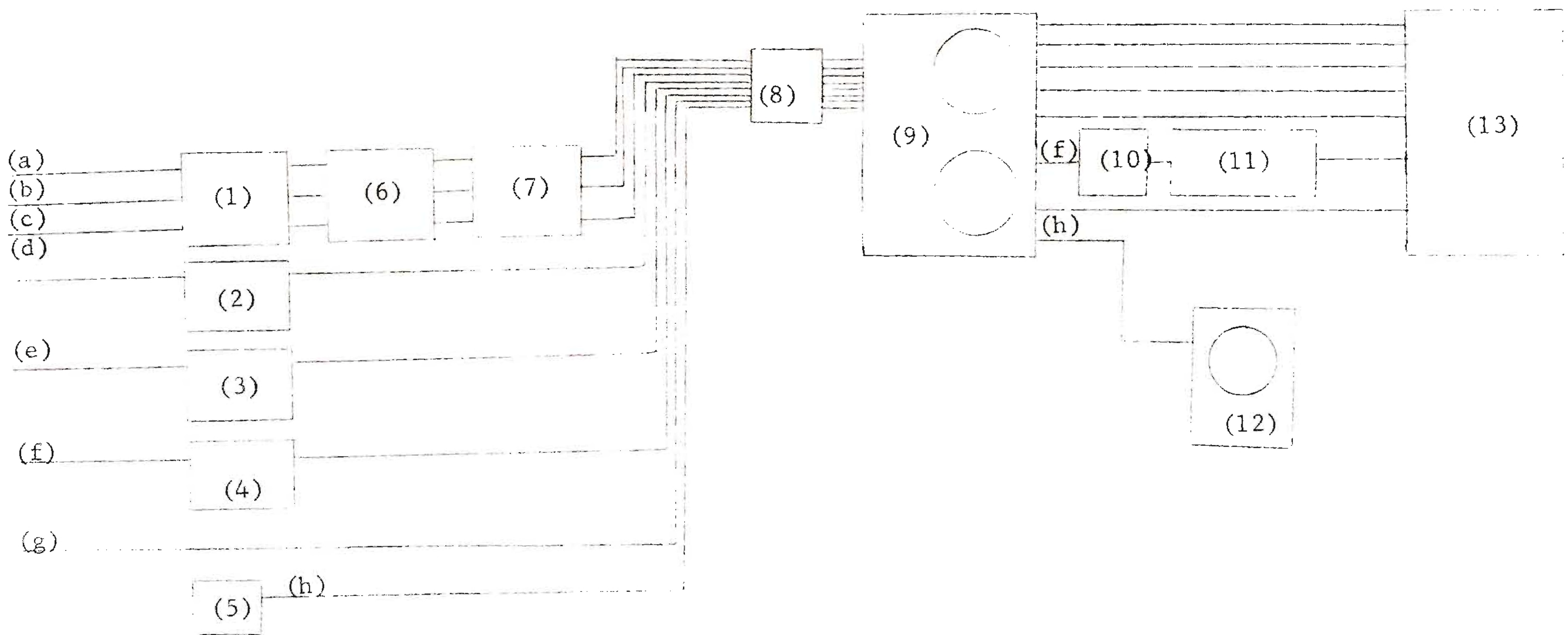

Fig. 1. Schematic of the Data Acquisition System.

Legend (Figure 1)

(a), (b), (c): Temperatures (inlet air, 1 ft above combustion bed, and flue gas)

(d), (e): CO and CO_2 concentrations

(f): Pressure amplitude

(g): Feed rate

(h): Line to locate position in the tape

(1): Thermocouple reference junction

(2), (3): CO and CO_2 infrared analyzers

(4): Microphone amplifier

(5): Wave generator

(6): Millivolt potentiometer (for calibration only)

(7): DC amplifier

(8): DC voltmeter (calibration of tape)

(9): Tape recorder

(10): RMS voltmeter

(11): Logarithimic connverter

(12): Oscilloscope

(13): x - y ploter

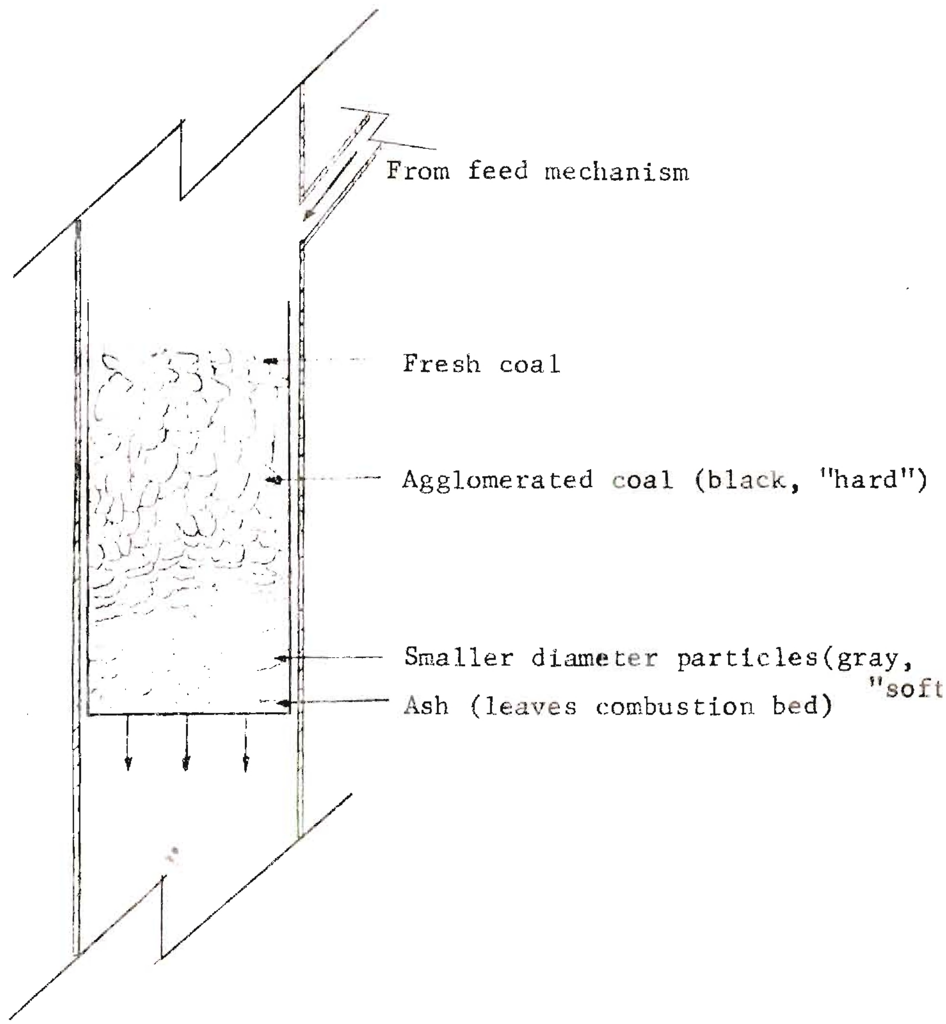

Fig. 2. A Schematic of the Bed Structure in the Pulsating Combustor.

E-16-604

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Ben T. Zinn
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November 10, 1981

Mr. Harry Ritz
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Pittsburgh, PA 15236

Subject: Progress report for the period October 1 through October 31, 1981 for work conducted under Contract DE-A 505-79-ER-10068.

Part of the efforts expended during the last reporting period concentrated on the evaluation of the pulsating combustor's performance for stoichiometric air flow rates and fuel feed rates varying between 70 gr/min and 100 gr/min (56.1 lbs/ft^2 hr and 80.2 lbs/ft^2 hr). Pulsating combustion was possible with all of the tested feed rates. However, the combustion efficiency at the 100 gr/min feed rate was approximately 5% lower than at the 75 gr/min feed rate (reported during the month of September). It is believed that the decrease in combustion efficiency at the high fuel feed rate was due to excessive heating of the combustor's walls, which resulted in an "effective" upward shift of the center of the region of heat addition from the "ideal" L/4 position. It is believed that this problem can be alleviated by lowering of the combustion bed and/or cooling of the combustor's wall near the combustion region. The average coal size in all of the tests ranged between 1/4 to 1/2 inches. The maximum amplitude of pulsation observed during these tests was 160 dB. The heat release for the 100 gr/min case was approximately 960,000 Btu/fr^2 hr. Comparison of the tests results showed that for conducted test conditions the combustor efficiency was the highest (i.e., approximately 90-92%) for feed rates around 70-75 gr/min when burning coal at a stoichiometric air/fuel feed rate. The heat release rate corresponding to this feed rate is approximately 750,000 Btu/ft^2 hr.

During this reporting period a new continuous feed system for coal and other solid fuels has been developed. In addition, a new test section, coal bed support grid and observation windows have been developed and they will be incorporated into the combustor in the near future.

During the next reporting period, tests will be conducted to determine the dependence of the combustor's performance on the air/fuel ratio. The initial series of tests will be conducted with a fixed coal feed rate of about 50 gr/min and varying flow rates of air that would allow testing under both fuel rich and fuel lean conditions.

Sincerely,

Ben T. Zinn

BTZ/rk

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Ben T. Zinn
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December 7, 1981

Mr. Harry Ritz
Mail Stop 920-208
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Pittsburgh, PA 15236

Subject: Progress report for the period November 1 through November 30, 1981 for work conducted under Contract DE-A-505-79-ER-10068.

During the last reporting period, a new test section containing a new fuel bed support grid and new observation windows was incorporated into the pulsating combustor. Testing with the new test section indicated that the presence of the new bed support system changed the characteristics of the combustion process and that the installation of new circular windows eliminated all the air leaks that existed with the previous, rectangular, window. Furthermore, the new configuration improved the combustor's performance in the following aspects: (1) the maximum amplitude of the combustor pulsations increased form 160 dB to 168 dB; (2) the amounts of unburned refuse that drops to the bottom was reduced by 50% as compared to the previously used test section; (3) accumulation of coal in the bed was practically eliminated; and (4) the observed rapid heat up of the combustor's walls suggests improvement in the associated heat transfer processes.

On the negative side, the amount of particles in the exhaust seemed to have increased considerably. The causes for this increase are believed to be understood and steps for correcting this problem will be taken shortly.

Tests with fuel feed rates of around 50 gr/min and stoichiometric air flow rates were performed. The combustion efficiency ranged between 87% and 90%. It was also observed that the amounts of particulates and carbon monoxide in the exhaust flow varied periodically with time. The carbon monoxide concentrations varied between 0% and 4% by volume with the maximum coinciding with the maximum in the particulate concentration. These maxima occur shortly after the feeding of fresh coal to the bed and they were probably caused by changes in the effective, instantaneous air/fuel ratio in the bed. The average coal size in all of the tests ranged from 1/4 to 1/2 inches.

During the next reporting period, series of tests with air/fuel ratios above and below the stoichiometric ratio will be performed with the new combustor's configuration. Air flow rates ranging from 0.4 to 2.0 times the air flow rate needed for stoichiometric combustion will be investigated. In addition, the development of an alternate fuel feed system that will provide a more uniform (with time) coal supply into the combustor will be undertaken.

Sincerely,

Ben T. Zinn

BTZ/jj

E-16-604

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January 21, 1982

Mr. Harry Ritz
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Subject: Progress report for the period December 1 through December 30, 1981 for work conducted under Contract DE-A-505-79-ER-10068.

During this reporting period, testing with the new combustion bed configuration that was described in last month's report was initiated. A series of experiments was conducted for air/fuel ratios varying from 0.35 to 1.9 of the stoichiometric air/fuel ratio for nominal coal feed rates of 50 gr/min. Both pulsating and non pulsating tests were performed and the results compared.

A plot of the measured pulsations dB level is presented in Fig. 1. Interestingly, maximum amplitudes were attained near stoichiometric operation. It was also observed in these tests that are increased in the dB level during a given test was accompanied by an immediate decrease and increase in CO and CO_2 concentrations, respectively. The latter are caused by the increase in the amplitude of the acoustic velocity in the bed region which results in better mixing and a more efficient combustion process. Thus, Fig. 1 suggests that optimum mixing and combustion occur near stoichiometric conditions. The significance of this result is that pulsating combustors could be operated optimally with little excess air, achieving high thermal efficiencies.

Another point to note in Fig. 1 is that pulsating operation is possible under highly fuel rich conditions (e.g., $\alpha = 0.36$). Under these conditions the exhaust flow is still combustible and this result suggests that the pulsating combustor can be potentially operated as a coal gasifier.

A plot showing the relative amounts of particulates generated under different air/fuel ratios is presented in Fig. 2 for both pulsating and non pulsating tests. A drastic reduction in particulates formation with an increase in α is shown with the particulate formation reaching an almost constant minimum level for a α larger than 1.1. One should also note that for all of the tested α's, particulate formation was considerably higher under non pulsating operation.

The measured CO and CO_2 data were also used to determine the combustion efficiency η of the combustor for different test conditions. Starting with stoichiometric test conditions, the results showed that η is 89 and 96 % for values of α equal to 1.03 to 1.13, respectively. As expected, the values of η increased with increasing values of α. For comparison, η equaled 87.4 % for $\alpha = 1.09$ when the combustor operated under non pulsating conditions.

Since the existing feed system resulted in periodic coal feed to the bed, a temporary feed system that resulted in nearly uniform coal feed rate to the bed was installed and tested. The results showed that the produced CO and the CO_2 concentrations nearly coincided with the minimum CO and maximum CO_2 concentrations, respectively, observed in the previously described tests. These results indicate that maximum performance of the pulsating combustor would be achieved once a uniform (permanent) coal feed mechanism is incorporated in the system. The installation of this new feed mechanism will be initiated during the next reporting period.

Sincerely,

Ben T. Zinn

BTZ/jj

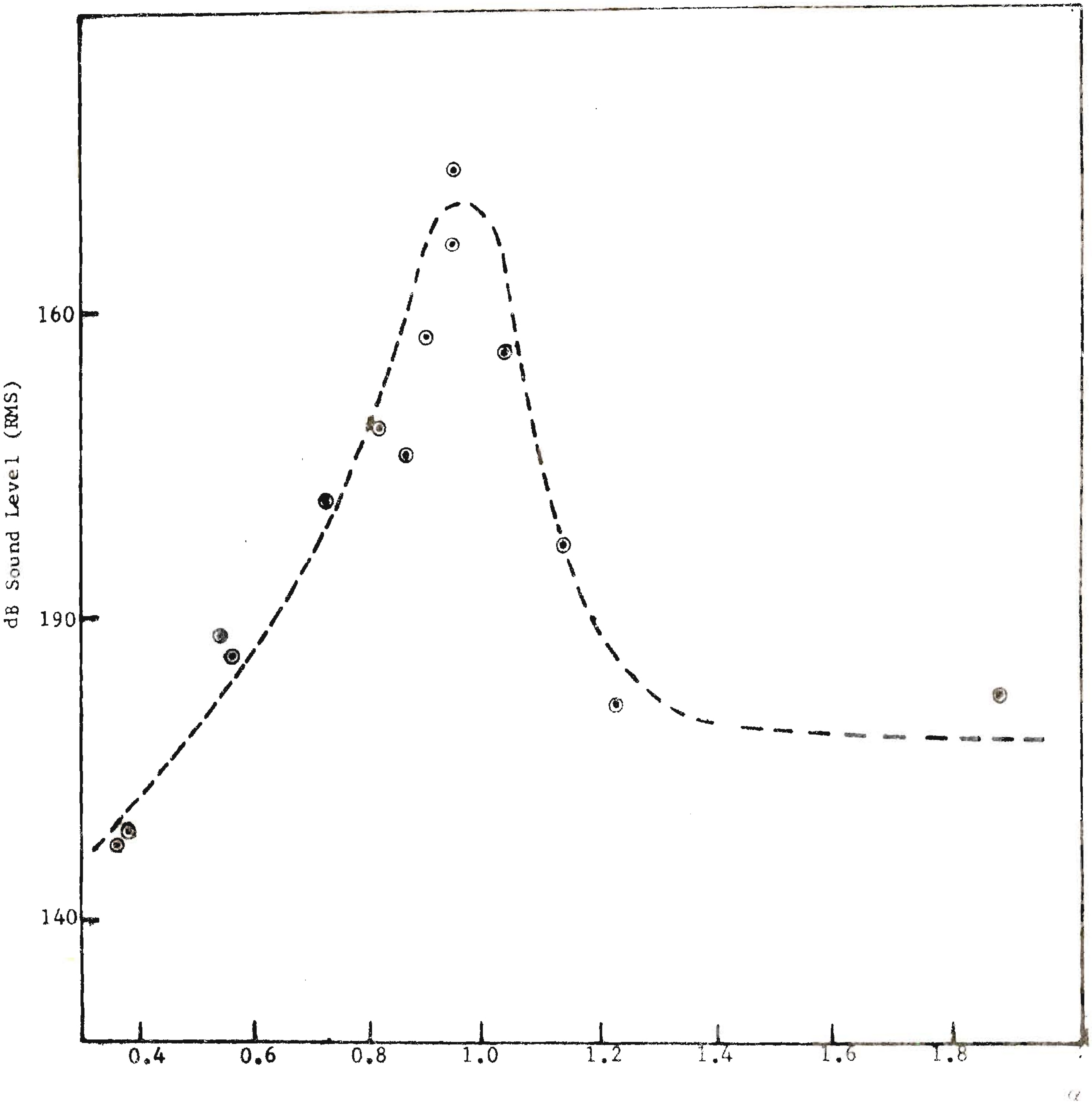

Fig. 1. Dependence of the dB sound level upon the air fuel ratio, nominal m_c = 50 gr/min (α : ratio between air/fuel ratio and stocihiometric air fuel ratio; m_c: feed rate of coal).

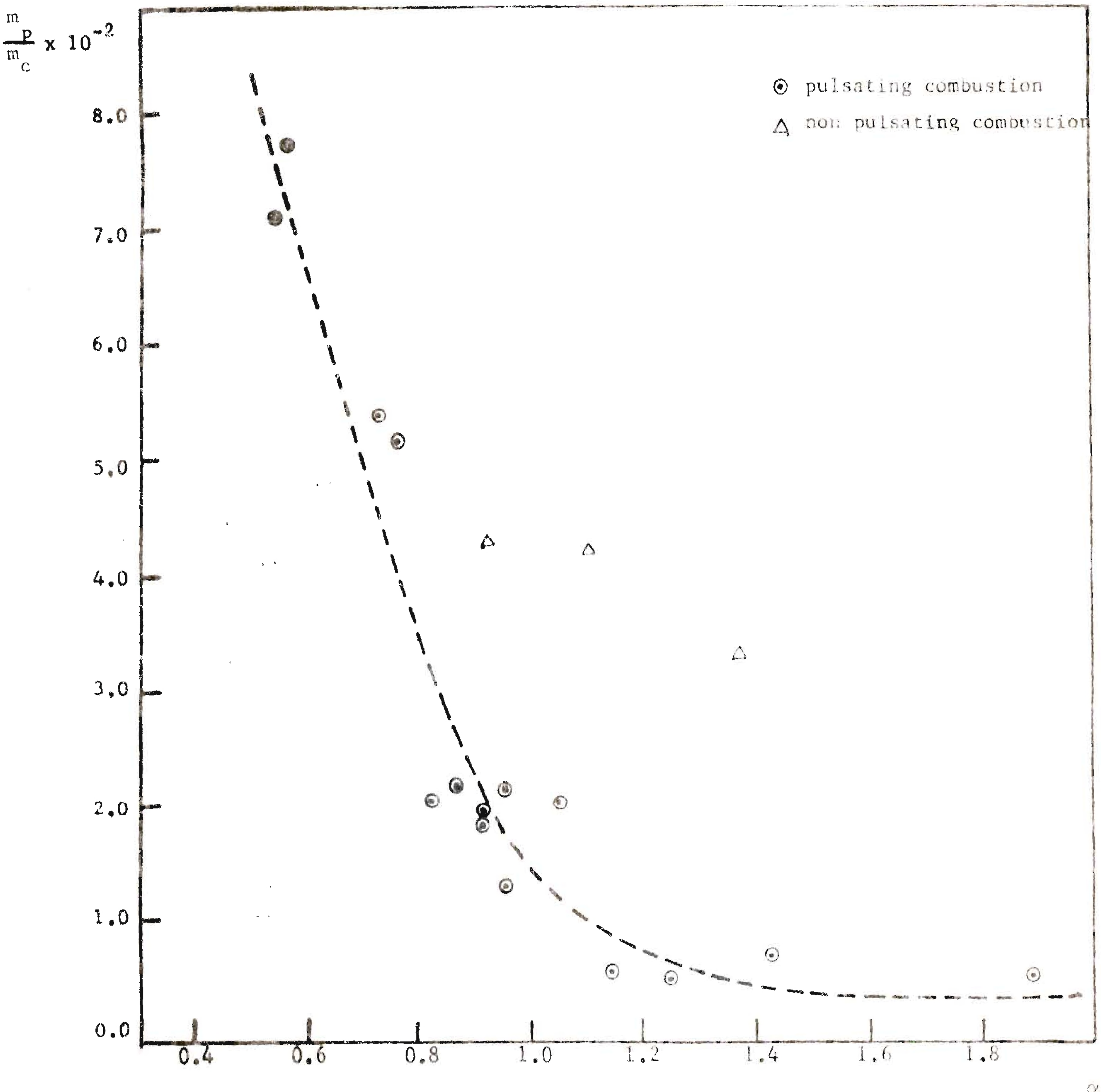

Fig. 2. Dependence of the particulate generation upon the air fuel ratio (m_p/m_c : ratio between collected mass of particulates and feed rate of coal).

E-16-604

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February 11, 1982

Mr. Harry Ritz
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Subject: Progress report for the period January 1 through January 31, 1982 for work conducted under Contract DE-A-505-79-ER-10068.

During the last reporting period, the previously developed auger type fuel feed mechanism was modified in order to provide a more uniform coal feed rate into the combustion bed. With the previous fuel feed system, as illustrated in the upper left part of Fig. 1, the coal feed rate was periodic, which was mainly due to the inclination of the feed tube that housed the rotating auger that moved the solid fuel from the hopper to the combustion bed. With the inclined feed tube, chunks of coal "fell" into the combustion bed as soon as they reached the end of the auger. The supply of coal into the bed was directly related to the speed of rotation of the auger and a "chunk" of coal was supplied to the bed upon the completion of each revolution. While the supply of coal was periodic, the air flow rate through the bed was constant. Consequently, fuel rich conditions occurred in the bed at regular intervals which resulted in periodic concentrations of CO and CO_2 and bursts of particulates in the exhaust flow. The modified feed mechanism possesses a horizontal feed tube, which is expected to practically eliminate the problems associated with the effects of gravity upon the coal supply rate. In addition, a new auger with a reduced pitch (half of the previously utilized auger's pitch) was introduced into the system. Together, these modifications are expected to produce a much more uniform coal feed rate into the combustion bed, as illustrated by the dashed line in the plot at the lower part of Fig. 1, resulting in more uniform CO and CO_2 concentrations and in the elimination of the bursts of particulates in the exhaust flow. Testing with the modified coal feed system will be initiated during this reporting period.

Two technical papers describing results obtained under this program to date were prepared during the last reporting period. The first, entitled "Development of a Pulsating Combustor for Burning of Wood", will be presented at the Symposium on Pulse-Combustion Applications, organized by the Battelle Laboratories, and to be held in Atlanta, on March 2-3, 1982. The second paper, entitled "Pulsating Combustion of Coal in a Rijke Type Combustor", was submitted for presentation at the 19th International Symposium on Combustion, organized by The Combustion Institute, and to be held on August 8-13, 1982, in Haifa, Israel.

During the next reporting period, installation of the new feed mechanism will be completed and its performance will be tested. Planned experiments will continue the evaluation of combustion efficiencies and dB level of pulsations for different combustor's operating conditions.

Sincerely,

Ben T. Zinn

BTZ/jj

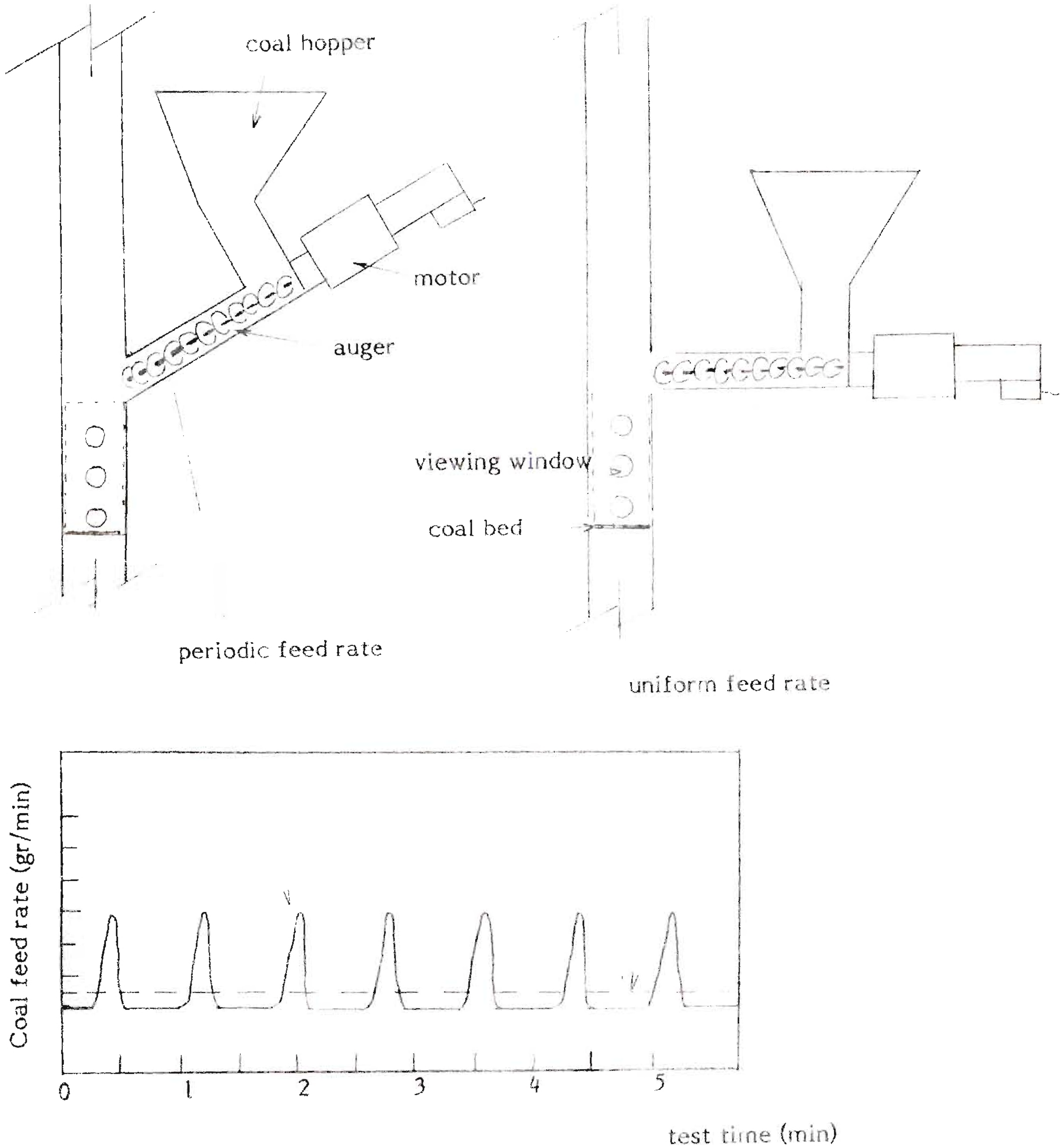

Figure 1. Schematics of the previously designed and the modified Coal Feed Systems and their feed rates.

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March 8, 1982

Mr. Harry Ritz
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Subject: Progress report for the period February 1, through February 28, 1982 for work conducted under Contract DE-A-505-79-ER-10068.

During this reporting period, the installation of the new coal feed system (described in last month's progress report) was completed and testing was initiated to check the operation of the modified combustor. First, experiments were conducted for stoichiometric air/fuel ratio at a nominal fuel feed rate of 50 gr/min. With the new feed system the previously observed periodicity of the feeding process was practically eliminated and the exhaust flow appeared clear and smokeless. Furthermore, the exhaust flow was free of the periodical bursts of particulates that had occurred with the inclined, auger type system that was used before. Drastic reductions in particulates emission and of both the maximum and average CO concentrations in the exhaust flow were observed. The average amplitude of pulsations remained at 162 dB. A comparison of the results obtained using the previous and new coal feed systems is presented in Table I.

In addition, a series of experiments whose concern is the determination of the maximum coal burn rate in the new combustor under stoichiometric conditions was started during this reporting period. Tests with nominal feed rates of 75 gr/min were conducted and the main results are described in what follows. First, an average sound level of 168 dB was observed, which represents the highest average amplitude of pulsations ever achieved with the developed pulsating combustor. Under this dB level, the coal was consumed shortly after entering the combustion bed and no accumulation of unburned fuel in the bed was ever observed. On the negative side, bursts of particulates in the exhaust flow reappeared. These bursts were not periodic and they were not caused by the coal feed system. The data measured during these tests are currently under analysis in an effort to eliminate the observed bursts of particulates

During the next reporting period the investigation of the maximum coal burn rate by the developed pulsating combustor under stoichiometric air/fuel ratio will continue. Additional tests with excess air will be performed in order to investigate the possibility of decreasing pollutants formation while taking advantage of the high dB level observed for increased coal feed rates. Finally, efforts will begin on the modification of the existing gas sampling lines to incorporate the NO_x and SO_2 sampling capabilities for use in future tests.

Sincerely,

Ben T. Zinn

BTZ/jj

	Previous inclined auger feed system	Present horizontal auger feed system	Variation
CO(%)(Maximum)	4.13	1.77	- 2.36
CO(%)(Average)	1.30	0.30	- 1.00
Particulate emission (gr/min)	0.958	0.139	- 0.819 (-85.5%)
dB level (Average)	162	162	0

Table I. Comparison between combustor operations with periodic and uniform feed rates, for stoichiometric nominal 50 gr/min coal feed rates and pulsating regime.

E-16-604

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April 12, 1982

Mr. Harry Ritz
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Subject: Progress report for the period March 1, 1982 through March 31, 1982 for work conducted under Contract DE-A-505-79-ER-10068.

Part of the work conducted during this reporting period was concerned with the determination of the maximum coal burn rate in the developed pulsating combustor under stoichiometric air/fuel ratio operation. Experiments were performed for nominal feed rates in the range 50-90 gr/min (which corresponds to 40-72 lb/ft^2hr) and the results are summarized in Table I. These results indicate that as the nominal feed rate is increased, while the air/fuel ratio is kept stoichiometric, the CO and particulate concentrations and particulate emission in the exhaust products also increase. These increases may be related to the associated increase in the mean flow velocity that is required to maintain a stoichiometric fuel/air ratio in the combustion bed and they are currently under investigation. One should also note that the average sound dB levels observed during this series of tests was higher than those observed with the previous combustor configuration as described in last February's progress report. In the present tests the dB level reached a maximum for a feed rate 75 gr/min. At this feed rate no bursts of particulates in the exhaust flow and no accummulation of unburned material in the coal bed were observed. One should also note that after reaching a maximum at 75 gr/min, the dB level decreases as the coal feed rate is further increased. In addition, the increase in the feed rate from 75 to 90 gr/min causes a more drastic increase in the CO and particulates concentrations in the exhaust flow. These observations are consistent with to the argument that the intensity of the pulsations exerts a strong influence upon the efficiency of the combustion process. Despite the higher losses at higher loads, a maximum heat release of approximately 856,000 Btu/ft^2 hr was achieved. This result compares very favorably with results reported in the literature for maximum heat releases in state of the art combustors (e. g., see Hardesty, D. R. and Pohl, J. H.: "The Combustion of Pulverized Coals - An Assessment of Research Needs," Vol. I, SAND 78-8804, Sandia Laboratories, January 1979). Current efforts are concerned with the development of an understanding of the mechanisms responsible for the trends of the data in Table I.

In addition, this group participated in the Symposium on Pulse-Combustion Applications, co-sponsored by the Gas Research Institute, DOE, and Battelle-Columbus Laboratories, that was held in Atlanta last month. Some results obtained to date under this program were presented in the conference in a paper entitled "Development of a Pulsating Combustor for Burning of Wood".

During the next reporting period, current efforts that are concerned with the elucidation of the relative importance of the various mechanisms that control the combustion of coal in the developed pulsating combustor will continue.

Sincerely,

Ben T. Zinn

BTZ/jj

Table I. Performance of the Pulsating Combustor for different Coal Feed Rates under Stoichiometric Conditions.

Nominal coal feed rate (gr/min)	50	58	65	75	90
dB level (average)	162	161	165	166	162.5
CO (%) (Maximum)	1.30	1.59	2.58	2.54	6.11
CO (%) (Average)	0.30	0.32	0.94	1.33	1.96
Particulate emission (gr/min)	0.14	0.58	1.34	2.11	4.75
% losses (CO and particulates)	1.3	2.3	5.6	8.0	13.1
Approximate heat release (10^3 Btu/ft^{2}hr)	550	624	678	780	856

C-16-604

DOE Annual Report on

DEVELOPMENT OF COAL BURNING PULSATING COMBUSTOR FOR POWER GENERATION

Prepared for

Department of Energy

Pittsburgh Energy Technology Center

by

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DOE Contract No. DE-AS05-79ER 10068

May 1982

ABSTRACT

This report describes the progress made under DOE Contract DE-AS05-79ER 10068 that terminated on September 30, 1981. The research conducted under this program consisted of an investigation of the burning of coal in a pulsating mode of combustion in a combustor whose design is based upon the Rijke tube principles. The combustor consists of a vertical tube opened at both ends with a fuel burning bed located in the middle of its lower half. In this configuration, the heat released by the combustion process spontaneously excites the fundamental, longitudinal acoustic mode of the tube. This study demonstrated that the combustor constructed under this program can burn coal stably and continuously under either the self aspirating or the forced flow modes of operation. In the latter case, maximum amplitudes occur near stoichiometric air/fuel ratio operation, indicating that systems utilizing the developed combustor or a similar version should possess high thermal efficiencies. Additionally, it was verified that pulsating operation is possible for a variety of air/fuel ratios, including fuel rich conditions, which suggests that the developed combustor could be used as a coal gasifier. Finally, carbon monoxide, carbon dioxide, and particulates concentrations in the exhaust flow were measured. The determined carbon monoxide and carbon dioxide concentrations were used to evaluate combustion efficiencies which ranged between 89 and 98.5% for air/fuel ratios between 1.03 and 1.22, respectively.

INTRODUCTION

This report describes progress made under a research program entitled "Development of Coal Burning Pulsating Combustor for Power Generation" that was supported under DOE Contract DE-AS05-79ER 10068 during the period October 1, 1980 to September 30, 1981. The research activities undertaken under this contract have been concerned with the investigation of the feasibility of burning coal under a pulsating mode of combustion and the determination of the major operational characteristics of the developed, Rijke-like pulsating combustor.

As the name implies, the combustion process in a pulsating combustor takes place under pulsating (i.e., oscillatory) conditions, implying that the various flow properties (e.g., pressure, velocity, etc.) at different locations in the combustion oscillate with a given frequency that is a characteristic of the developed combustor. In contrast, the flow conditions are basically constant in conventional combustors. As it is discussed in more detail below, interest in the burning of coal under pulsating conditions stems from its potential advantages that include:

(1) highly intense combustion process;
(2) considerably improved convective heat transfer characteristics;
(3) reduced pollutants formation;
(4) ability to burn unpulverized coal;
(5) self aspiration;
(6) ability to reduce slagging and keep heat transfer surfaces clean; and
(7) ability to burn coal with little excess air.

While various combinations of the above listed advantages have been demonstrated to date in applications involving pulsating combustion of gaseous (e.g., see Refs. 1-4) and liquid[1,5] fuels, none of these advantages have been demonstrated consistently in applications of the pulsating combustion process in the burning of coal and/or other solid fuels*.Consequently, the investigation described in this report had been undertaken with the objective of determining whether a coal burning pulsating combustor that is capable of incorporating into its design as many of the above listed advantages as possibly could be developed.

Efforts conducted to date on the application of pulsating combustion in the burning of coal include the studies of Severyanin[6] and Hanby[7] that deal with the development of experimental combustors; Sommers[8] that describe a full scale application in Germany in the 1950s; and Lyman[9] who studies individual coal particles combustion under pulsating conditions. In addition, Ref. 1 contains several conceptual papers that discuss the development of coal burning pulsating combustors. All of the experimental efforts to date utilized pulverized coal and their design was either identical or representative of the well known Schmidt tube[1] design that provided the foundation for the well known V1 "Buzz Bomb" that was developed by the Germans during the second world war. Before proceeding with the discussion of the results of the coal studies[6-9], a brief discussion of some of the

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* The principal investigator of this project has been told of such studies in the Soviet Union, but no written descriptions of such studies could be found in the English literature.

characteristics of the Schmidt Tube are in order. In this case it can be shown that in order to achieve a pulsating mode of combustion, the characteristic combustion time (that may include the characteristic times of vaporization, mixing, chemical kinetics and so on processes) must be of the order of half the period of oscillation of the combustor. Qualitatively, this requirement[1,10,11] is due to the fact that in order to achieve a pulsating mode of combustion in a Schmidt tube, the heat release due to combustion needs to occur during the phase of maximum pressure in the combustor. Since in the Schmidt tube the fuel and oxidizer are injected into the combustor near the phase of pressure minimum (see Fig. 1), the time available for combustion between the injection instant and the instant of maximum pressure (when the combustion should occur) is approximately half the period of the oscillation, which explains the above stated criterion.

Satisfying the above stated time condition

$$\tau_{\text{combustion}} \sim \frac{1}{2} T \tag{1}$$

does not appear to present any difficulties when gaseous fuels are involved and various pulsating combustors that utilize such fuels have been developed to date[1-4]. However, as one changes from gaseous to liquid to solid fuels the combustion time becomes longer due to the "addition" of such processes as heating, vaporization, surface combustion and so on into the combustion process and satisfying Eq. (1) above becomes more difficult[5-7]. In the case of pulverized coal combustors, attempts to resolve this difficulty usually involved various schemes for preheating the fuel in order to shorten the

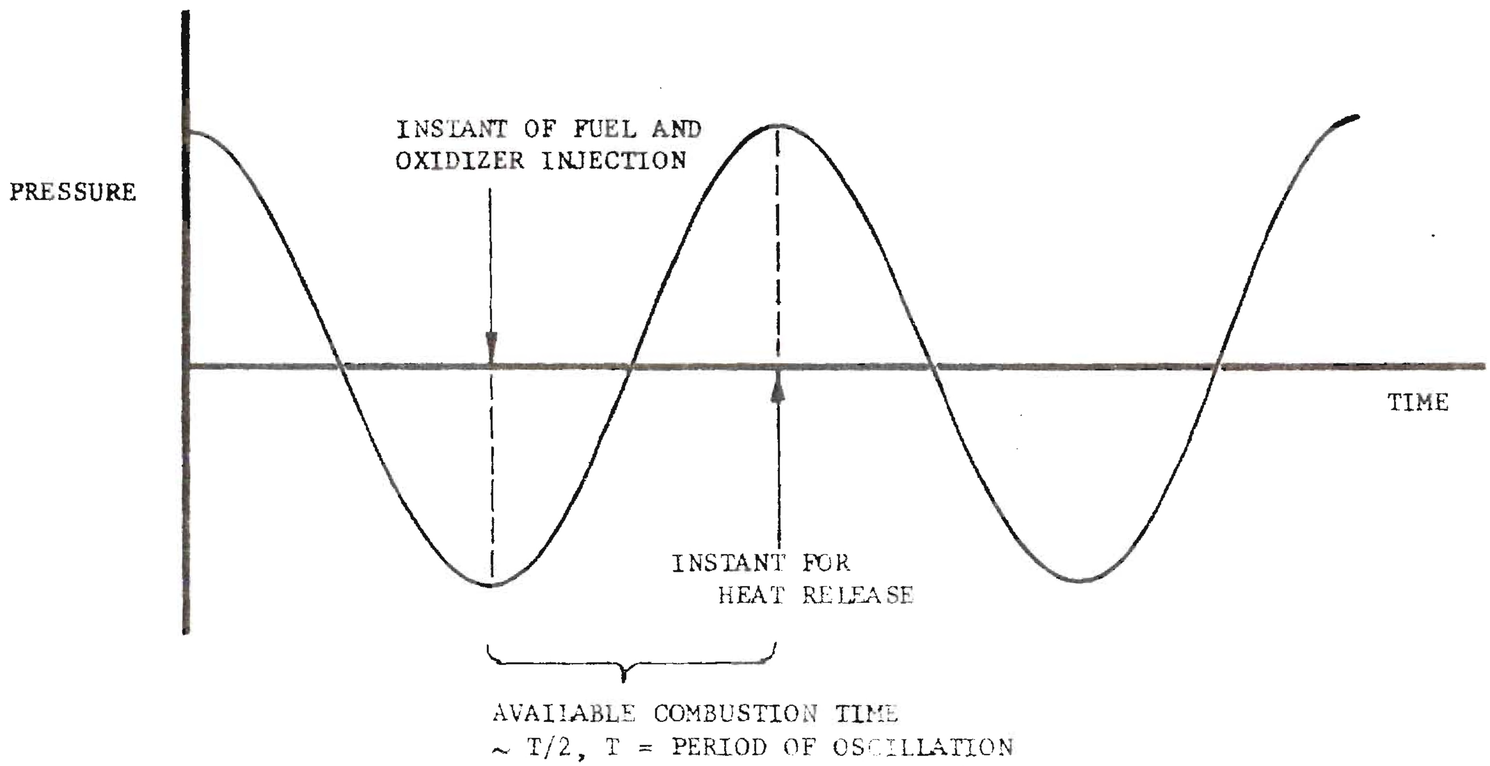


Figure 1. Qualitative Description of "Required" Combustion Time for Pulsating Combustion in a Schmidt Tube.

combustion time[6,7]. When the coal was not preheated, the developed combustors suffered from such problems as inability to stabilize the combustion process, incomplete combustion, and difficulties in maintaining pulsating combustion for different fuel/air ratios, and efforts to resolve these difficulties have resulted in cumbersome combustor design. Consideration of these problems at the initiation of this program had lead this group to the conclusion that burning coal in a Schmidt type pulsating combustor is bound to experience difficulties and the decision was made at the time to proceed with the development of a coal burning pulsating combustor that would be based upon the radically different Rijke tube oscillator[12]. As is described in the next section, results obtained to date under this program indeed demonstrate that the Rijke-like combustor developed by this group is capable of successfully burning coal and other solid fuels under a pulsating mode of combustion over wide ranges of operating conditions.

Next, before proceeding with the discussion of the characteristics of the pulsating combustor that was developed under this program, it would be appropriate to provide evidence in justification of claimed advantages of the pulsating combustion process, as listed under items (1) through (7) earlier in this section.

1. Highly Intense Combustion Process. In Schmidt type pulsating combustors and in the one developed under this program the occurrence of pulsating combustion is associated with the presence of acoustic velocity oscillations in the combustor in addition to a steady flow velocity component. The acoustic velocity component changes directions at a rate

that equals the frequency of pulsations and it is believed to greatly enhance the rate of mixing of fuel and oxidizer in the combustor, resulting in a high rate of combustion.

Additional explanation that has been advanced in the literature[1] for the high combustion rates of coal particles in pulsating combustors is the periodic stripping of the blanket of combustion products that surrounds the coal particle by the oscillating acoustic velocity. This action reduces the gas phase resistance (that is provided by the blanket of combustion products) to the migration of oxygen molecules toward the coal particle surface, resulting in the acceleration of the coal particle combustion. The above argument was based upon the notion that a coal particle is surrounded by a layer of combustion products after the initial phase of volatiles combustion. Recent combustion studies at Sandia[13] seem to indicate, however, that the particle and the blanket of combustion products tend to "separate" before the coal particle is completely burned even in the absence of pulsations. While this may appear to contradict the argument advanced in this paragraph, it is nevertheless plausible that the presence of pulsations enhances the stripping of the combustion products layers from the coal particles.

While there may be some questions regarding the exact mechanism(s) responsible for the high rate of coal burning due to pulsations, evidence provided by Sommers[8] and Lyman[9] who studied pulverized coal combustion clearly supports this claim. Finally, as will be discussed in the next section, our own work to date in this area indicates that the pulsating combustion process is characterized by a very high combustion rate per unit area (i.e.,

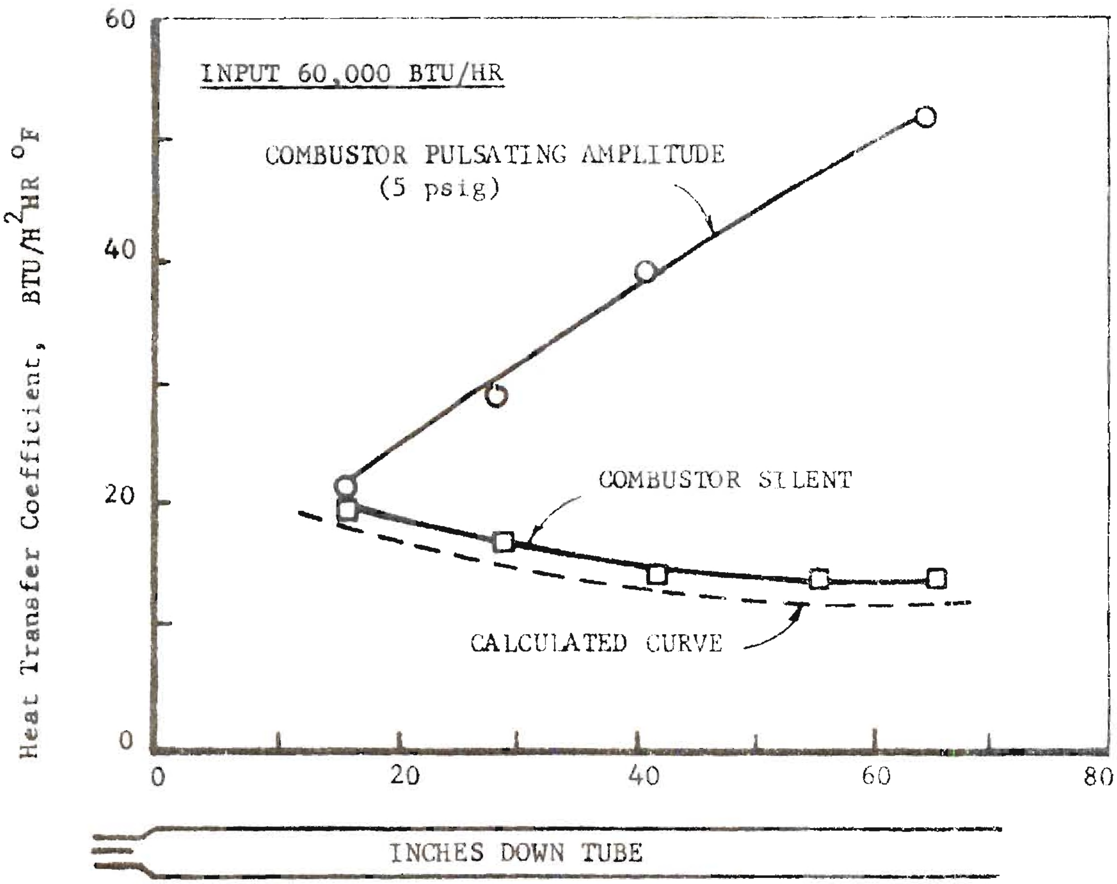


Figure 2. The Effect of Oscillations on the Distribution of Heat Transfer Coefficient in the Combustor.

Btu/ft^2hr).

The implication of a high combustion rate is that the resulting combustor will be smaller in size requiring a smaller initial capital investment.

2. Improved Heat Transfer Characteristics. The presence of acoustic oscillations is apparently responsible for considerably increased convective heat transfer from the flow to the surrounding boundaries. This phenomenon is well known and it had been responsible in the past for the melting of the walls of liquid propellant rocket motors after the onset of combustion instability. A good discussion of this phenomenon is provided by Hanby[14] and the resulting improvement in the convective heat transfer coefficient is described in Fig. 2 that was taken from Ref. 14. Figure 2 shows that the heat transfer coefficient depends upon the local flow conditions and that it reaches a maximum at a location of maximum acoustic velocity amplitude near the exit of the combustor. Comparing the plots provided in Fig. 2 for the heat transfer coefficients under pulsating and nonpulsating conditions clearly indicates the improved heat transfer processes that are associated with pulsating operation.

In practical terms, the improved heat transfer that is associated with the presence of acoustic velocity oscillations indicates that a given amount of heat can be transferred over a smaller heat transfer area, implying the need for a smaller heat exchanger and a smaller initial capital investment.

3. Reduced Pollutants Formation. This claim is supported by related studies conducted in the U. S. and the U. S. S. R. with pulsating combustors that utilized gaseous and liquid fuels. Reference 15 describes a Russian

investigation that specifically dealt with this problem. In this study, pollutants formation in two different combustor designs were compared under pulsating and nonpulsating (i.e., turbulent) operating conditions utilizing gaseous and liquid fuels. In all of the investigated cases, the results show reductions in the production of nitrogen oxides, carbon monoxide, hydrocarbons, sulfur dioxide and soot as a result of transition from nonpulsating to pulsating operation, with the reductions being significant (i.e., orders of magnitude) in most cases. In this case, the reduction in the production of carbon monoxide, hydrocarbons and soot also indicates that the presence of pulsations results in a more complete combustion process (i.e., higher combustion efficiency) which also supports some of the arguments advanced under item (1) above. Another point that needs to be emphasized is that pollutants reductions were observed while burning both gaseous and liquid fuels, suggesting that similar benefits might also occur during pulsating combustion of solid fuels.

Additional support for reduced nitrogen oxides formation during pulsating combustion is provided in the work of Belles[2] that deals with pulsating combustion of gaseous fuels. The following is a quote from Ref. 2 that describes these results: "Fortunately, our measurements show that the NO_x emissions of pulse burners are considerably lower than those of conventional furnaces, both in absolute concentration and also in terms of mass emitted per unit of usable heat appear to be real and they are most encouraging".

While the above observations need to be further investigated, especially for coal combustion, they nevertheless indicate that the use of pulsating combustion may reduce the production of pollutants to levels that will eliminate the need for complex combustor designs (e.g., combustion staging; see Ref. 16) and/or the incorporation of some expensive pollutants removal procedures or equipment into the system, resulting in reductions in both operational and/or capital investment costs.

4. Ability to Burn Unpulverized Coal. This is a characteristic of the Rijke-type pulsating combustor developed under this program and it is discussed in more detail in the next section. It's availability eliminates the need for investing in the acquisition of pulverizers and the continuous pulverizing cost, thus reducing both capital investment and operational costs. This feature should be particularly attractive to industries that are considering a switch to coal utilization and are considering the cost of such a move.

5. Self Aspiration. This feature implies that the combustor can "pump" its own oxidizer eliminating the need for auxiliary fans and/or pumps that are utilized in conventional combustors for moving the oxidizer (i.e., air) through the combustor. This unique feature of pulsating combustors offers the possibility of eliminating the costs associated with the purchase and operation of the needed air pumping equipment.

Before leaving this section, it should be pointed out that pulsating combustors can be operated under both self aspirating and forced oxidizer flow conditions.

6. Reduced Slagging and Keeping that Heat Transfer Surfaces Clean. The acoustic velocity oscillations that are associated with the pulsating combustion process result in back-and-forth motions (of different

amplitudes) of the gases along the various combustor and heat transfer surfaces. According to the Russian literature[5,16] and physical intuition, this motion results in a scrubbing type action on the surface that reduces or prevents slagging and foreign material depositions along these surfaces. This scrubbing action of the acoustic velocity in pulsating combustors may provide an acceptable solution to this serious problem.

7. Ability to Burn with Little Excess Air. Conventional combustors operate with air/fuel mixtures that may contain up to forty percent more air than is required for stoichiometric combustion. The use of excess air results in a decrease in the thermal efficiency of the system due to the costs associated with the thermal losses in the exhaust products, the pumping the additional air and the energy lost in vaporizing the moisture content of the air. In addition, the excess air results in lower temperatures of the combustion products which may adversely affect heat transfer processes. Thus, it is desired to operate with as little excess air as possible. In studies conducted by this group and those described in Ref. 15 it has been found that maximum amplitude of pulsating combustors might be able to operate efficiently with little excess air, resulting in combustors having higher thermal efficiencies.

The above discussion describes the observed advantages of the pulsating combustion process that provided the impetus for this research program. It consisted of the development of the Rijke-like, coal burning, pulsating combustor and its testing under different operating conditions. The results of these efforts are described in the following section.

PROGRAM ACHIEVEMENTS

This section is divided into two parts with the first part providing the background for the Rijke tube combustor that has been utilized in this study and the second part briefly describing achievements under this program.

The Developed Rijke Type Combustor

One of the initial objectives of this program was the development of a coal burning pulsating combustor that would not suffer from the shortcomings of the earlier designs, as discussed in the Introduction Section. Considerations of the problems that needed to be resolved and a personal communication with Severyanin during a 1978 visit to the Soviet Union lead to the conclusion that a pulsating combustor based upon the Rijke Tube[12] principles may offer an attractive alternative to the previously used Schmidt tube-like combustor designs[6].

The Rijke Tube, which was first developed in the 19th century, is shown schematically together with its associated acoustic wave structure in Fig. 3. In this configuration, the metal gauze is heated either apriori by a flame or concurrently by an electric current. In either case the wire acts as a heat source that induces an upward steady flow in the tube due to natural draft and periodic heating of the gas that results in the excitation of the natural mode of the tube, whose structure is also shown in Fig. 3. Theoretical investigations of the operation of the Rijke tube have been conducted by Carrier[17] and Culick[18]. In both cases it has been argued that the normalized heat transfer perturbation $Q'/\bar{Q}$ is related to the

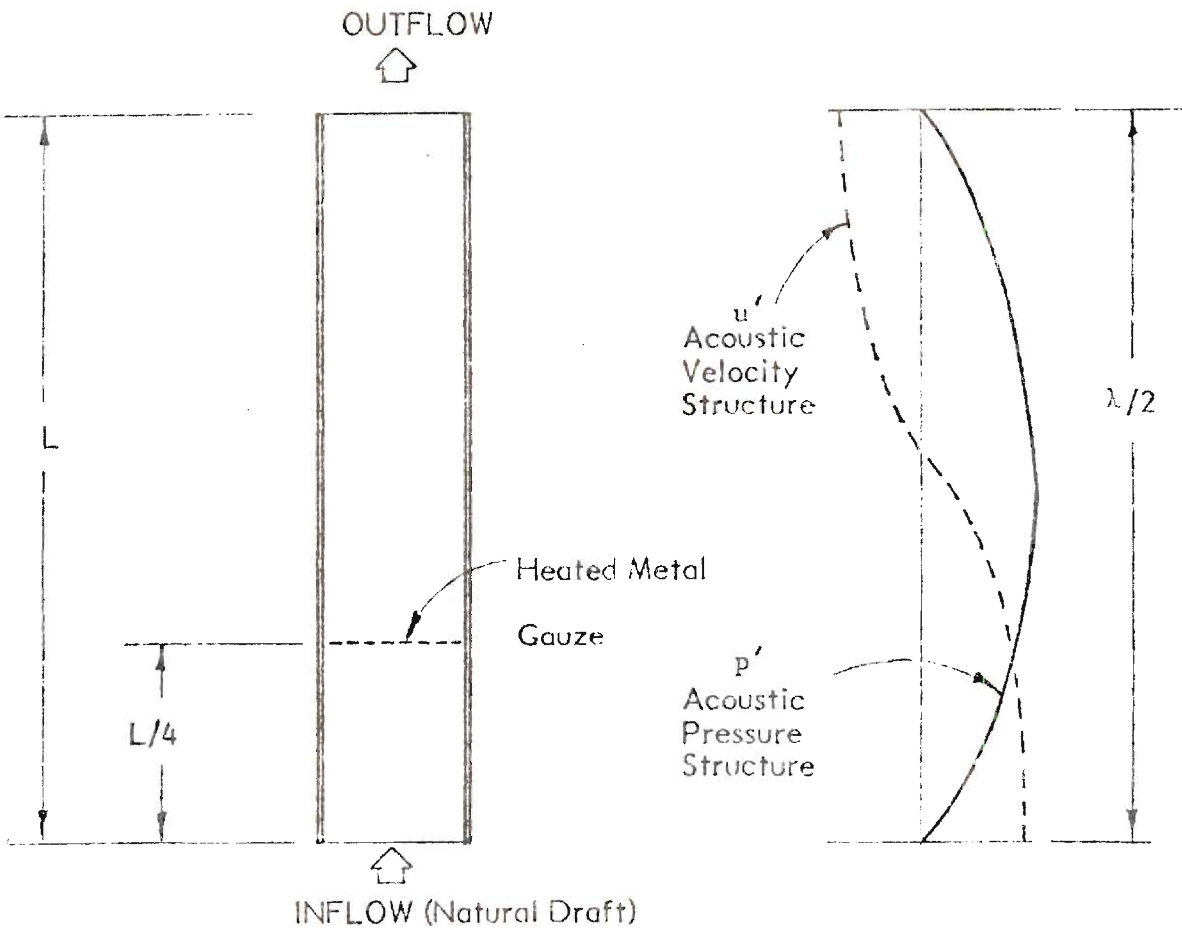


Figure 3. Schematic of the Rijke Tube

normalized velocity oscillation $(u'/\bar{a})$ via the relationship

$$Q'/\bar{Q} = qe^{-i\Psi}\,(u'/\bar{a}) \tag{2}$$

where Q is the heat transfer, q is a proportionality constant, Ψ is the phase difference between the heat addition and velocity perturbation and a the velocity of sound. The magnitude of the phase Ψ is of interest to the understanding of the physics of the problem. According to Ref. 17, $\Psi = 3\pi/8$ while according to Ref. 18 $0 \leq \Psi \leq \pi$.

Another point that needs to be emphasized is the importance of having a steady flow past the wire to the onset of an oscillation of the fundamental mode[18]. In the absence of such a flow, the frequency of any excited oscillation will be twice the frequency of the fundamental mode due to the fact that the heat transfer from the wire is proportional to the magnitude of the velocity and not its direction. On the other hand it can be shown that the presence of both a mean velocity and an oscillating velocity component may result in the excitation of the fundamental mode of the tube.

Additional experiments that influenced the present program were those conducted by Bosscha and Riess[10] in which hot flow was introduced into the bottom of a vertical tube and heat was removed from the flow at a distance 3L/4 from the bottom of the tube as shown in Fig. 4. As in Rijke's experiments, the removal of the heat at the indicated location resulted in the excitation of the fundamental mode of the tube as shown in Fig. 4. While it will not be done here, it should be pointed out that the Bosscha and

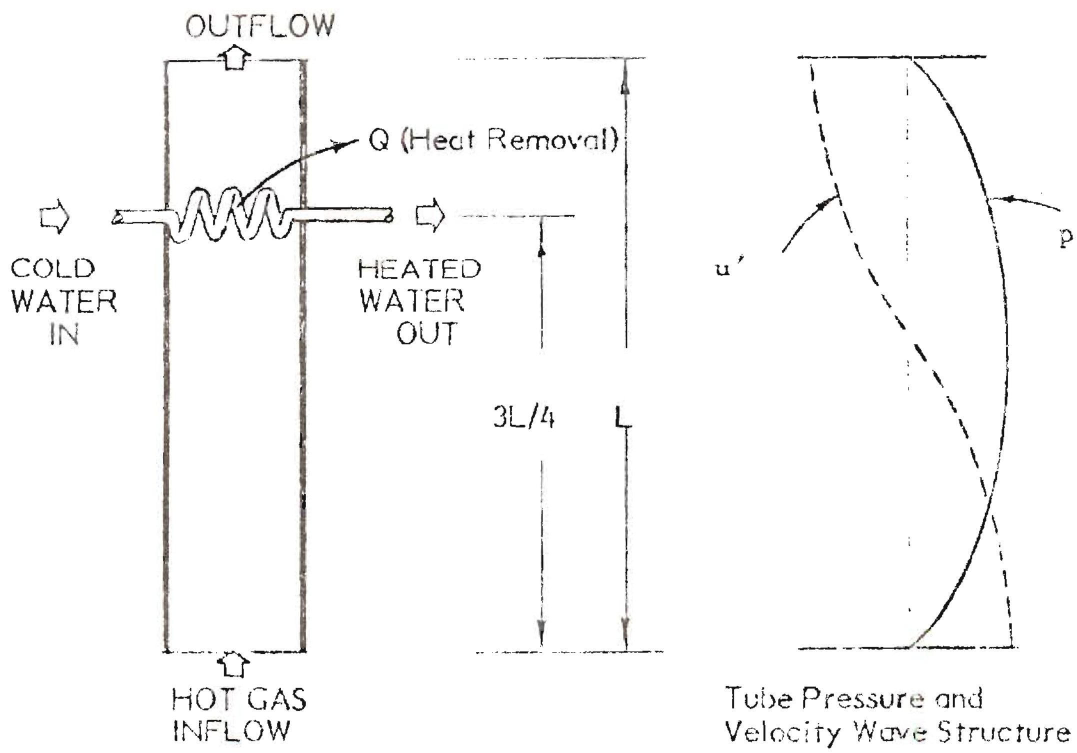


Figure 4. A Schematic of the Bosscha and Riess Experiments.

Riess experiments can be explained utilizing arguments similar to those used to explain the mechanisms responsible for the onset of the oscillation in the Rijke tube.

In summary, the Rijke, Bosscha and Riess experiments showed that the fundamental mode of a tube opened at both ends may be excited if heat is added at a distance of L/4 and/or removed at a distance of 3L/4 from the entrance of the tube. Keeping this in mind, a pulsating combustor could be designed by replacing the hot metal gauze by a coal burning bed at the L/4 position. While having a heat source at the L/4 position would be sufficient for obtaining a pulsating combustor, the pulsations would be amplified according to the Bosscha and Reiss experiments if heat is also removed from the hot combustion products at the 3L/4 position.

Summary of Accomplishments to Date

This section briefly summarizes the major accomplishments of this program to date. The objectives of this study were to (1) determine whether a coal burning pulsating combustor based upon the Rijke tube principles could be developed, and (2) determine the main operational characteristics of such combustor.

The developed Rijke tube pulsating combustor is shown in Fig. 5. It consists of cylindrical segments with internal diameter of 5.5" and wall thickness of 0.25". The total length is 108". Additional segments were built to permit variations in the combustor's length. Since the fuel remains in the bed over many cycles, this combustor does not suffer from the difficulties encountered in the previously discussed Schmidt type combustors in which

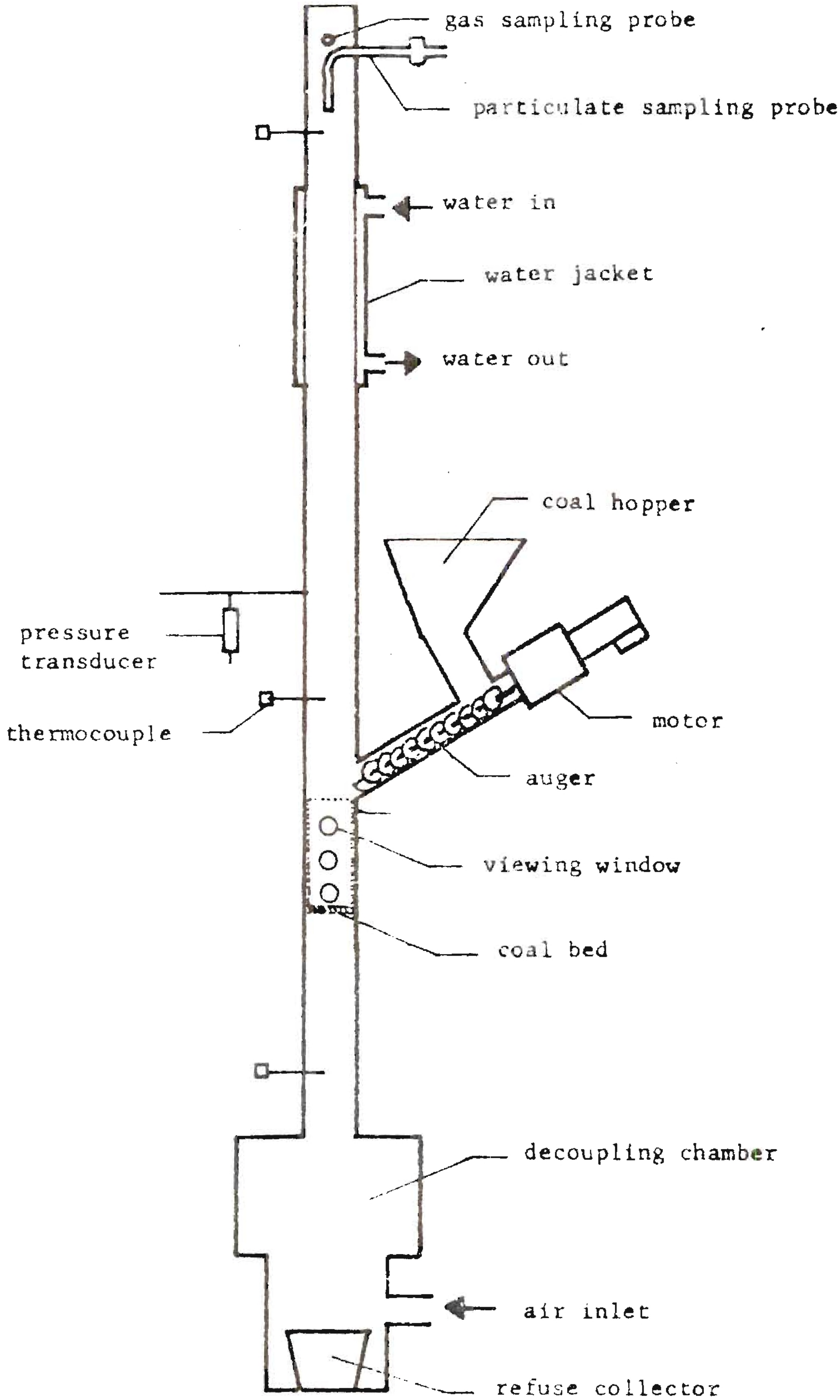


Figure 5. Schematic of the Developed Rijke Tube Pulsating Combustor.

preheating of the pulverized coal was required in order to satisfy the combustion time requirements. In this combustor configuration (see Fig. 5), coal is supplied to the combustion bed by means of a calibrated auger type feed system and pulsating combustion can be attained under either a self aspirating or a forced flow mode of operation. Under the forced flow mode, the decoupling chamber serves to guide the air into the combustor without altering the required open end boundary condition at the lower end. Coal was burned in a metal wire combustion bed located at L/4 and a water heating jacket was installed near the 3L/4 position. The lower decoupling chamber is disconnected from the tube when the combustor is operated under the self aspirating regime.

Developed measurement capabilities include thermocouple temperature measurements at different locations within the combustor, acoustic pressures using a condenser microphone, velocities using hot film, air flow rates during forced flow experiments using rotameters, high speed combustion zone photography utilizing specially designed viewing windows, coal feed rates utilizing a calibration curve of the auger type feed system, carbon monoxide and carbon dioxide gas concentrations at the exhaust flow using two Beckman model 864 infrared analyzers, and particulate emissions using a specially designed gas particulate sampling train. A sketch of the combined gas-particulate sampling train is shown in Fig. 6. The carbon monoxide and carbon dioxide gas concentration measurements in the exhaust flow provide data for the evaluation of the system's combustion efficiencies.

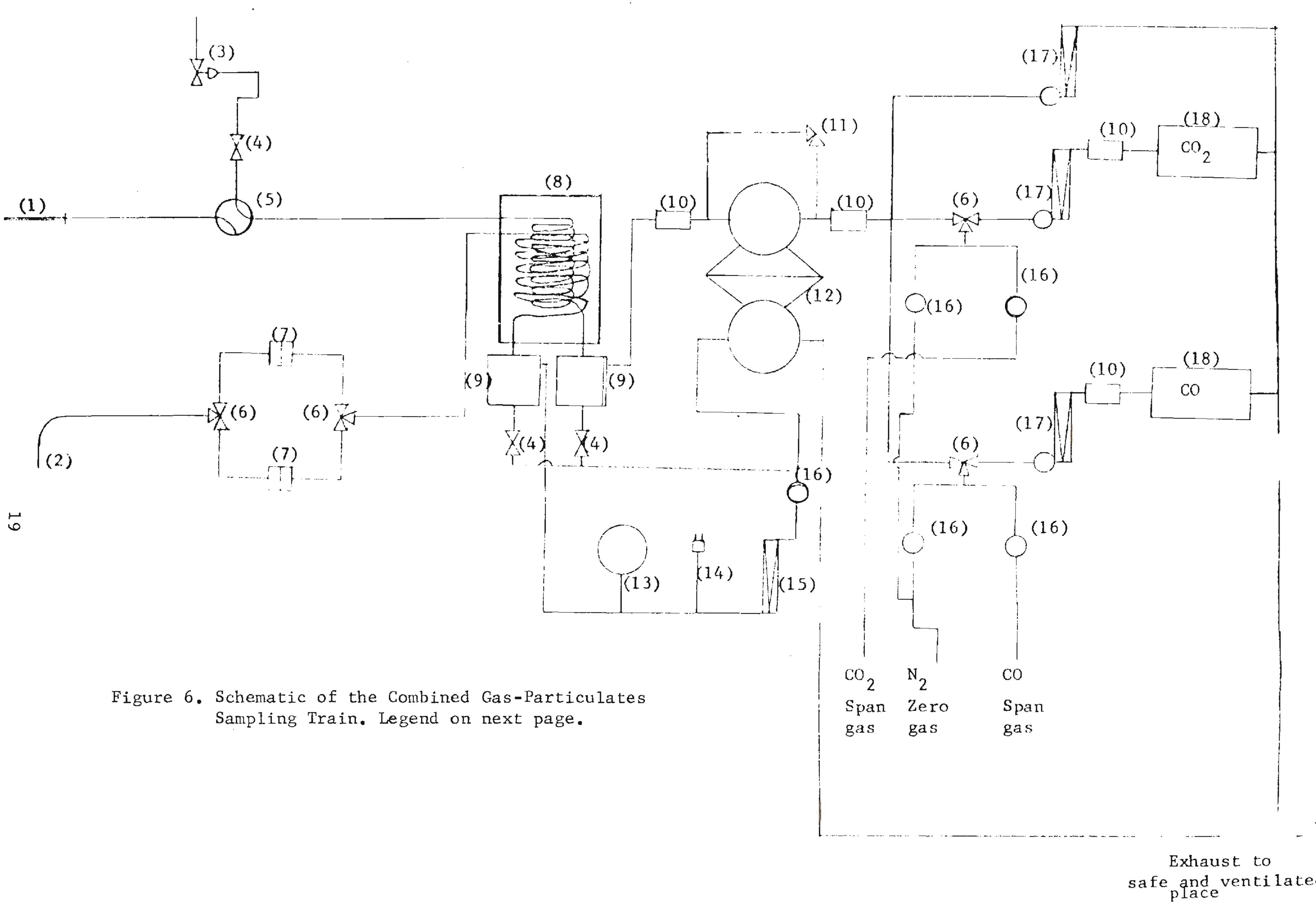


Figure 6. Schematic of the Combined Gas-Particulates Sampling Train. Legend on next page.

Legend (Fig.6)

(1) Cylindrical shape sintered metal filter (60) - gas sampling

(2) Nozzle type ½" diameter probe - isokinetic particulate sampling

(3) Pressure regulator with valve - purge system

(4) Two way valves

(5) Four way valve

(6) Three way valves

(7) Filter - retention of 99.7% of particles greater than 0.3

(8) Ice bath

(9) Separators

(10) Protection filters

(11) Relief valve

(12) Dual head pump

(13) Vacuum gauge

(14) Thermocouple

(15) Flowmeter

(16) Needle point valves

(17) Flowmeters with valve

(18) Infrared analyzers

In what follows, the major results obtained to date utilizing the above described experimental set up are briefly discussed.

1. Combustor Operation. This program has established that a Rijke type pulsating combustor can be utilized to burn coal and other solid fuels stably and continuously under either self aspirating or forced flow conditions. Pulsating combustion operation has been obtained consistently with the developed combustor within minutes after the ignition of the combustion bed.

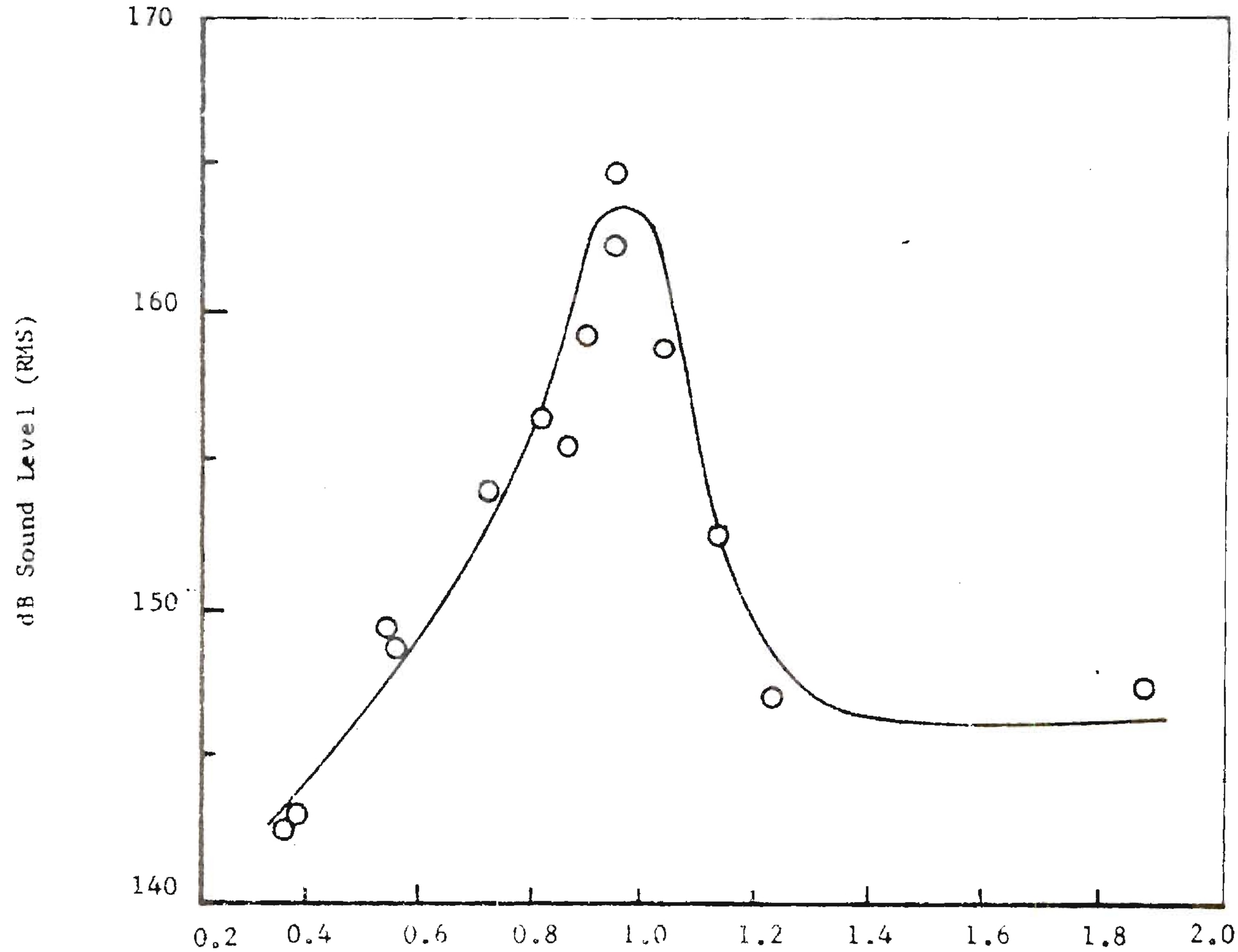
Utilizing a nine foot length combustor, results obtained to date showed that the frequency of pulsation was in the range 74 to 84 Hertz and that the pressure amplitude varied between 140 and 160 dB for operations under the self aspirating mode and between 150 and 165 dB for operations under the forced flow mode.

2. Characteristics of the Developed Pulsating Combustor. One measure of the performance of the developed combustor is the amplitude of the excited acoustic oscillation. In this case an increase in the amplitude implies better coupling between the combustion process and the natural acoustic mode of the combustor that should result in "better" mixing and consequently more efficient combustion process. In addition, the increase in amplitude may result in better heat transfer processes and reduced pollutants formation. Thus, measured dependence of the amplitude of the oscillation upon different combustor operating parameters has been used as an indication of the performance of the system with a higher amplitude operation implying a more "efficient" operation.

Tests conducted to date showed that the amplitude of pulsations depends upon the location of the combustion zone within the lower half of the tube. For a given combustion bed configuration the amplitude is near maximum when the bed is located a distance of L/4 from the entrance to the tube. Also, moving the bed to different positions results in the excitation of higher harmonics of the fundamental combustor mode.

The amplitude also depends upon the degree of accumulation of coal in the bed. For low or zero accumulation, acoustic energy dissipation in the bed is minimized and the amplitude of the combustor pulsations increases.The amplitude of the oscillation decreased as the length of the combustor was decreased. As a matter of fact maximum amplitude was obtained with the maximum tested combustor length of 9 feet. This result indicates that the various processes responsible for wave excitation and wave losses are frequency dependent and that there is an optimum frequency of operation for Rijke Tube Combustors. It appears that for the present combustor a further (small) increase in length may result in further amplitude increase. These results also indicate that an investigation of the optimum frequency of operation is desirable.

3. Forced Flow Operation. Pulsating operation under forced flow conditions permitted testing under a variety of air/fuel ratios. A series of tests were conducted with coal and wood for different air/fuel ratios and the results, plotted in Figs. 7 and 8, show that the amplitude of the oscillation strongly depends upon the air/fuel ratio with the maximum occurring near stoichiometric operation. These results are consistent with previous Russian



$$\alpha = \frac{(m_{Air}/m_{Fuel})_{Exp}}{(m_{Air}/m_{Fuel})_{Stoich}}$$

Figure 7. Measured Acoustic Pressure Amplitudes for Experiments Conducted with Coal Burned under Different Air/Fuel Ratio and Nominal Coal Feed Rate of 50 gr/min.

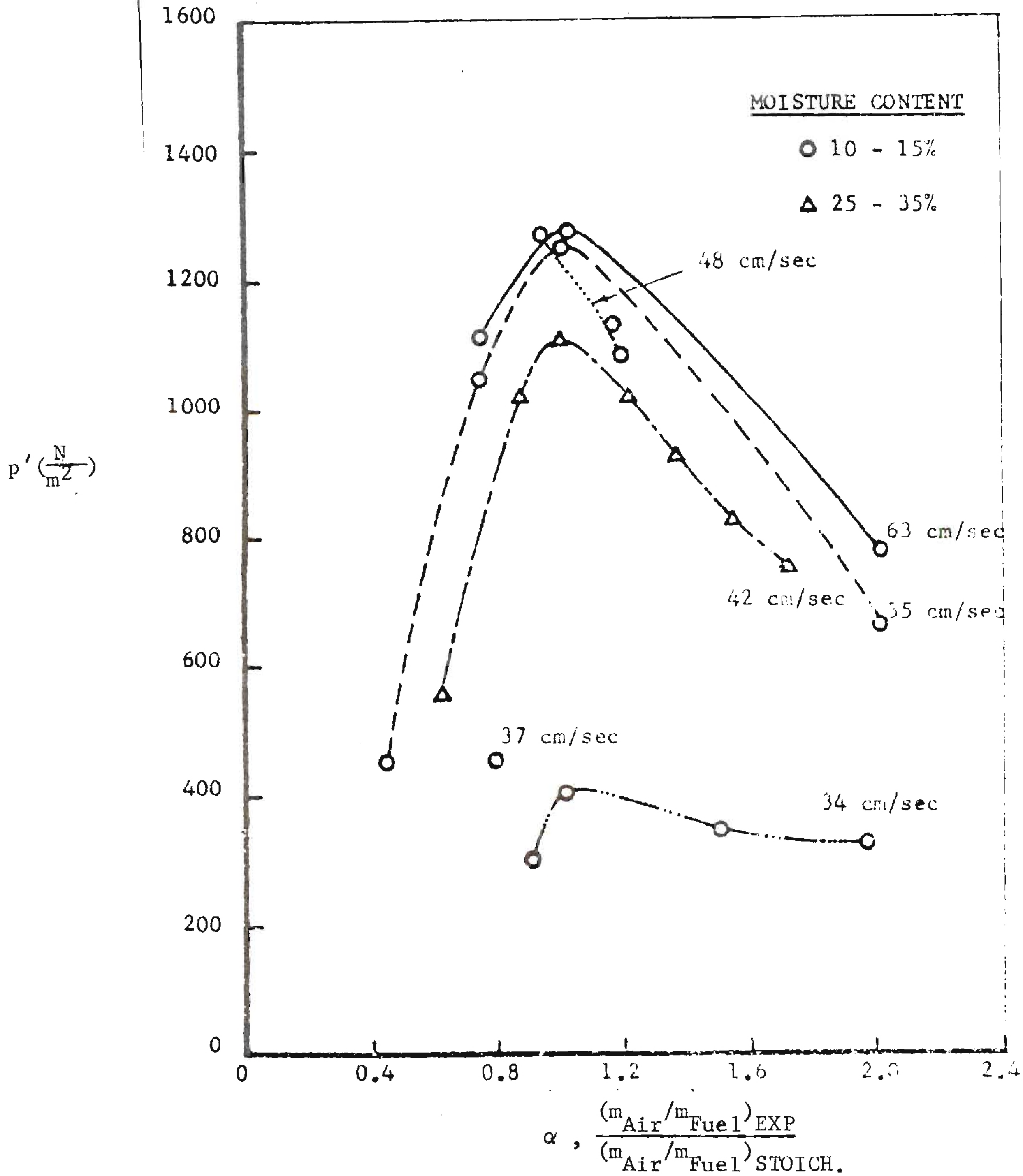


Figure 8. Measured Acoustic Pressure Amplitudes for for Experiments Conducted with Wood Burned under Different Air/Fuel Ratios and Different Steady Velocities.

results[15] and it supports the previous claim that the pulsating combustors could be operated with little excess air, resulting in higher thermal efficiencies for the combustor.

Figure 8 also indicates that the amplitude of the oscillation depends upon the magnitude of the steady state velocity $\bar{u}$, with the available data showing that an increase in $\bar{u}$ leads to an increase in the amplitude of pulsation. These data indicate that the coupling (i.e., driving) between the combustion process and the oscillation strongly depends upon the magnitude of the steady velocity through the combustion zone. This result also indicates that this coupling process needs to be further investigated and that forced flow operation which provides an independent control of the magnitude of $\bar{u}$ may be preferable in terms of providing means for controlling the operation of the pulsating combustor.

4. Fuel Rich Operation. Another significant aspect of the data presented in Figs 7 and 8 is the demonstration that pulsating combustion operation was achieved under fuel rich conditions (i.e., $\alpha < 1$). Since for $\alpha < 1$ the exhaust flow is fuel rich and it could possibly be used as a fuel, then these results suggest that the developed pulsating combustor, or a modified version, could be possibly used in solid fuel gasification applications.

5. Comparisons Beween Pulsating and Nonpulsating Operation. During the course of this study, it has been found that opening one or two small holes in the wall of the combustor tube a few inches above the combustion bed results in the cessation of the pulsations. This capability allowed for qualitative comparisons of the characteristics of the combustion zones and exhaust flows under pulsating and nonpulsating conditions. When the

combustor was pulsating, visual observations indicated that the luminous combustion zone was short exhibiting extremely intense "agitation" of the gases within the combustion zone. In addition, flamelets moving periodically downward (against the direction of the steady upward flow) through the holes of the wire mesh supporting the coal bed were observed. This downward motion was undoubtedly caused by the back-and-forth motion of the acoustic velocity near the combustion bed which is also responsible for intensified mixing within the combustion zone; the latter is probably responsible for the "compactness" of the observed combustion zone. In addition, the exhaust flow leaving the combustor appeared clear and smoke free.

When pulsations are absent, the combustion bed with the through air flow probably approximates the combustion in an stoker type combustor. In this case, observations of the fuel bed showed the presence of a relatively long luminuous combustion zone that "started" someplace near the middle of the bed and extended some distance above the bed. Furthermore, the combustion zone lacked the "intensity" or "vibrations" observed during pulsating combustion and there were no flamelets protruding below the wire mesh coal support. Finally, the presence of black smoke was clearly visible in the exhaust flow.

Also, comparisons of exhaust flows concentrations showed that the presence of pulsations reduces CO and concentrations while increasing CO_2 concentration, implying that pulsations result in a more complete combustion process.

The observed differences in the characteristics of the combustion zones and exhaust flows between the two modes of combustion strongly support the argument that the presence of acoustic velocity oscillations near the combustion bed during pulsations is responsible for intensified mixing and, consequently, more rapid and complete burning of the solid fuel in the bed.

6. Multiple Fuel Operations. To date, pulsating operation was studied under this program utilizing different commercially available coals (one of which was supplied by Georgia Power) and a variety of woods containing different amounts of moisture. While the amplitude of the resulting pulsation depended upon the characteristics of the fuel, pulsating operation was obtained in all instances. As a matter of fact, the combustor had no problems burning wood with forty percent moisture content and freshly cut wood, which cannot be readily burned in most combustors.

These observations together with earlier[19] successful operation of a Rijke tube combustor with a gaseous fuel suggest that Rijke type, pulsating combustors capable of multiple fuels operation, including low grade fuels (e.g., freshly cut wood), could be designed in the future.

7. Combustion Efficiencies. The carbon dioxide and carbon monoxide concentration measurements in the exhaust flow together with the measured air/fuel ratios, the determined coal composition (i.e., by ultimate analysis); and considerations of mass conservation were used to evaluate the combustions efficiencies of the system under different conditions in the forced flow mode of operation. For a coal feed rate of 50 gr/min and different air/fuel ratios, the combustion efficiency ranged from 89 to 98.5%

for values of α (i.e., the normalized air/fuel ratio) ranging from 1.03 to 1.22, respectively. The combustion efficiencies for corresponding non pulsating operations were always found to be lower (e.g., in some instances 15% lower) than the values determined for pulsating operation.

8. Combustion Intensities. Using the computed combustion efficiencies and measured coal feed rates the combustion process heat release rates were calculated. Maximum heat release rates of 750,000 Btu/hr ft^2 were achieved with stoichiometric operations, a value that compares very favorably with energy release rates of recent state of the art combustors[20].

9. Particulate Emission. A plot showing the relative amounts of particulates generated under different air/fuel ratios and nominal feed rate of 50 gr/min is presented in Fig. 9. A drastic reduction in particulates formation with an increase in α is observed with the particulates formation reaching an almost constant minimum level for α larger than 1.1. One should also note that for all of the tested α's, particulates formation was considerably higher under non pulsating operation.

Report Summary

The results obtained under this research program demonstrated that unpulverized coal can be burned continuously and stably in a Rijke type combustor. Under pulsating operation, the presence of acoustic oscillations enhances the mixing between oxidizer and fuel which increases the efficiency and heat release rate of the combustor. Maximum amplitudes occur when the air/fuel ratio is nearly stoichiometric which suggests that

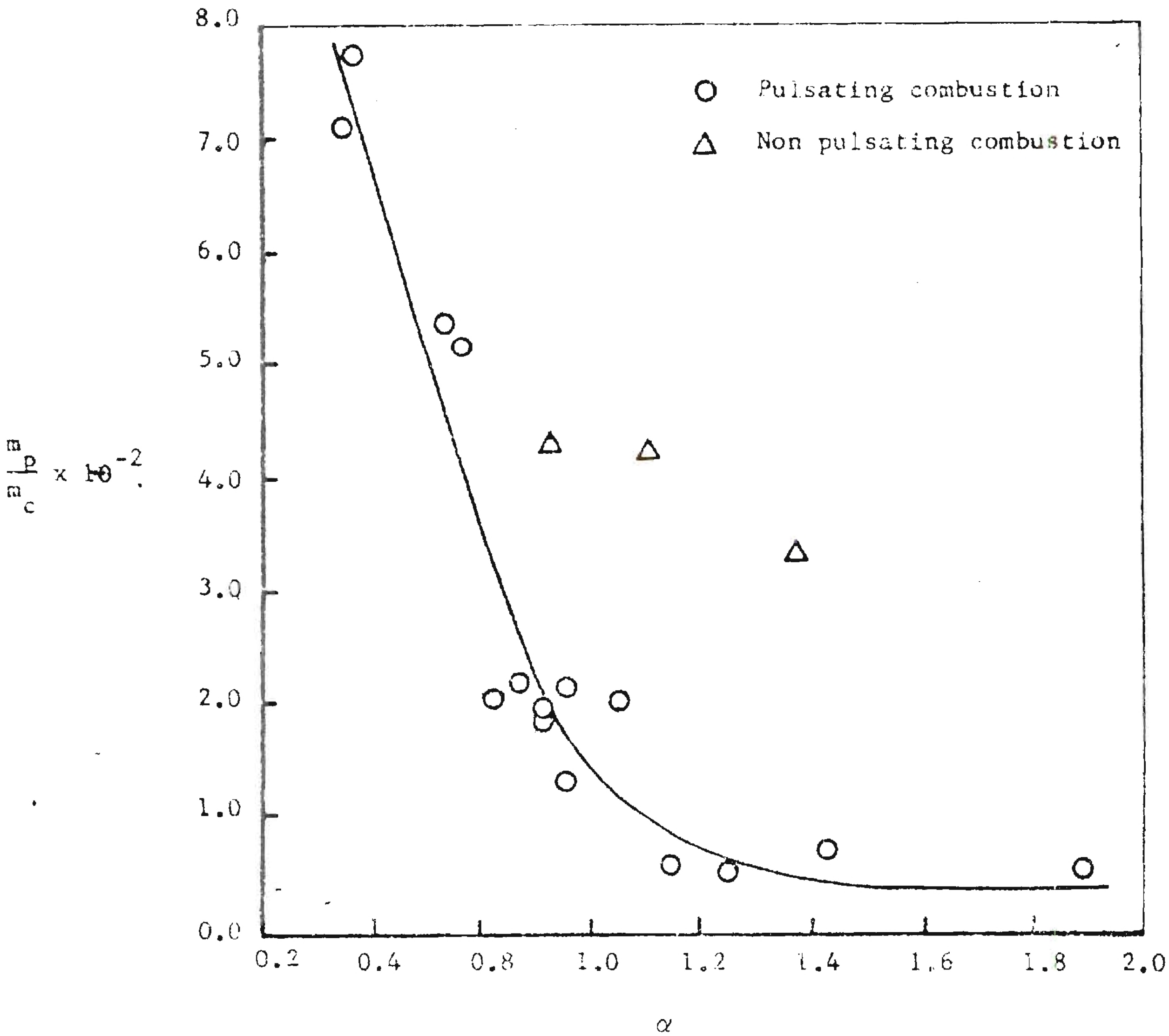


Figure 9. Dependence of the Particulate Generation upon the Air/Fuel Ratio for Nominal Feed Rates of 50 gr/min (m_p/m_c = ratio between collected mass of particulates and feed rate of the coal).

devices (e.g. boilers, water heaters, etc.) utilizing such a pulsating combustor should possess high thermal efficiencies. It was also verified that pulsating combustion operation of the developed combustor is possible for a variety of air/fuel ratios, including very fuel rich conditions (eg. = 0.36). Under these fuel rich situations, the exhaust flow is combustible indicating that the developed Rijke combustor could possibly be also utilized as a coal gasifier. In closing, the results obtained under this program to date demonstrate that with further development, Rijke type pulsating combustors may provide energy users with an attractive means for deriving energy from coal.

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DEVELOPMENT OF COAL BURNING PULSATING COMBUSTOR FOR POWER GENERATION

By

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Nehemia Miller
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Prepared for

DEPARTMENT OF ENERGY
PITTSBURGH ENERGY TECHNOLOGY CENTER

Under

DOE Contract No. DE–AS05–79ER 10068

December 1982

GEORGIA INSTITUTE OF TECHNOLOGY
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF AEROSPACE ENGINEERING
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ABSTRACT

This report describes the progress made under DOE Contract DE-AS05-79ER 10068 that terminated on September 30, 1981. The research conducted under this program consisted of an investigation of the burning of coal in a pulsating mode of combustion in a combustor whose design is based upon the Rijke tube principles. The combustor consists of a vertical tube opened at both ends with a fuel burning bed located in the middle of its lower half. In this configuration, the heat released by the combustion process spontaneously excites the fundamental, longitudinal acoustic mode of the tube. This study demonstrated that the combustor constructed under this program can burn coal stably and continuously under either the self aspirating or the forced flow modes of operation. In the latter case, maximum amplitudes occur near stoichiometric air/fuel ratio operation, indicating that systems utilizing the developed combustor or a similar version should possess high thermal efficiencies. Additionally, it was verified that pulsating operation is possible for a variety of air/fuel ratios, including fuel rich conditions, which suggests that the developed combustor could be used as a coal gasifier. Finally, carbon monoxide, carbon dioxide, and particulates concentrations in the exhaust flow were measured. The determined carbon monoxide and carbon dioxide concentrations were used to evaluate combustion efficiencies which ranged between 89 and 98.5% for air/fuel ratios between 1.03 and 1.22, respectively.

INTRODUCTION

This report describes progress made under a research program entitled "Development of Coal Burning Pulsating Combustor for Power Generation" that was supported under DOE Contract DE-AS05-79ER 10068 during the period October 1, 1980 to September 30, 1981. The research activities undertaken under this contract have been concerned with the investigation of the feasibility of burning coal under a pulsating mode of combustion and the determination of the major operational characteristics of the developed, Rijke-like pulsating combustor.

As the name implies, the combustion process in a pulsating combustor takes place under pulsating (i.e., oscillatory) conditions, implying that the various flow properties (e.g., pressure, velocity, etc.) at different locations in the combustion oscillate with a given frequency that is a characteristic of the developed combustor. In contrast, the flow conditions are basically constant in conventional combustors. As it is discussed in more detail below, interest in the burning of coal under pulsating conditions stems from its potential advantages that include:

(1) highly intense combustion process;

(2) considerably improved convective heat transfer characteristics;

(3) reduced pollutants formation;

(4) ability to burn unpulverized coal;

(5) self aspiration;

(6) ability to reduce slagging and keep heat transfer surfaces clean; and

(7) ability to burn coal with little excess air.

While various combinations of the above listed advantages have been demonstrated to date in applications involving pulsating combustion of gaseous (e.g., see Refs. 1-4) and liquid[1,5] fuels, none of these advantages have been demonstrated consistently in applications of the pulsating combustion process in the burning of coal and/or other solid fuels*.Consequently, the investigation described in this report had been undertaken with the objective of determining whether a coal burning pulsating combustor that is capable of incorporating into its design as many of the above listed advantages as possibly could be developed.

Efforts conducted to date on the application of pulsating combustion in the burning of coal include the studies of Severyanin[6] and Hanby[7] that deal with the development of experimental combustors; Sommers[8] that describe a full scale application in Germany in the 1950s; and Lyman[9] who studies individual coal particles combustion under pulsating conditions. In addition, Ref. 1 contains several conceptual papers that discuss the development of coal burning pulsating combustors. All of the experimental efforts to date utilized pulverized coal and their design was either identical or representative of the well known Schmidt tube[1] design that provided the foundation for the well known V1 "Buzz Bomb" that was developed by the Germans during the second world war. Before proceeding with the discussion of the results of the coal studies[6-9], a brief discussion of some of the

* The principal investigator of this project has been told of such studies in the Soviet Union, but no written descriptions of such studies could be found in the English literature.

characteristics of the Schmidt Tube are in order. In this case it can be shown that in order to achieve a pulsating mode of combustion, the characteristic combustion time (that may include the characteristic times of vaporization, mixing, chemical kinetics and so on processes) must be of the order of half the period of oscillation of the combustor. Qualitatively, this requirement[1,10,11] is due to the fact that in order to achieve a pulsating mode of combustion in a Schmidt tube, the heat release due to combustion needs to occur during the phase of maximum pressure in the combustor. Since in the Schmidt tube the fuel and oxidizer are injected into the combustor near the phase of pressure minimum (see Fig. 1), the time available for combustion between the injection instant and the instant of maximum pressure (when the combustion should occur) is approximately half the period of the oscillation, which explains the above stated criterion.

Satisfying the above stated time condition

$$\tau_{\text{combustion}} \sim \frac{1}{2} T \tag{1}$$

does not appear to present any difficulties when gaseous fuels are involved and various pulsating combustors that utilize such fuels have been developed to date[1-4]. However, as one changes from gaseous to liquid to solid fuels the combustion time becomes longer due to the "addition" of such processes as heating, vaporization, surface combustion and so on into the combustion process and satisfying Eq. (1) above becomes more difficult[5-7]. In the case of pulverized coal combustors, attempts to resolve this difficulty usually involved various schemes for preheating the fuel in order to shorten the

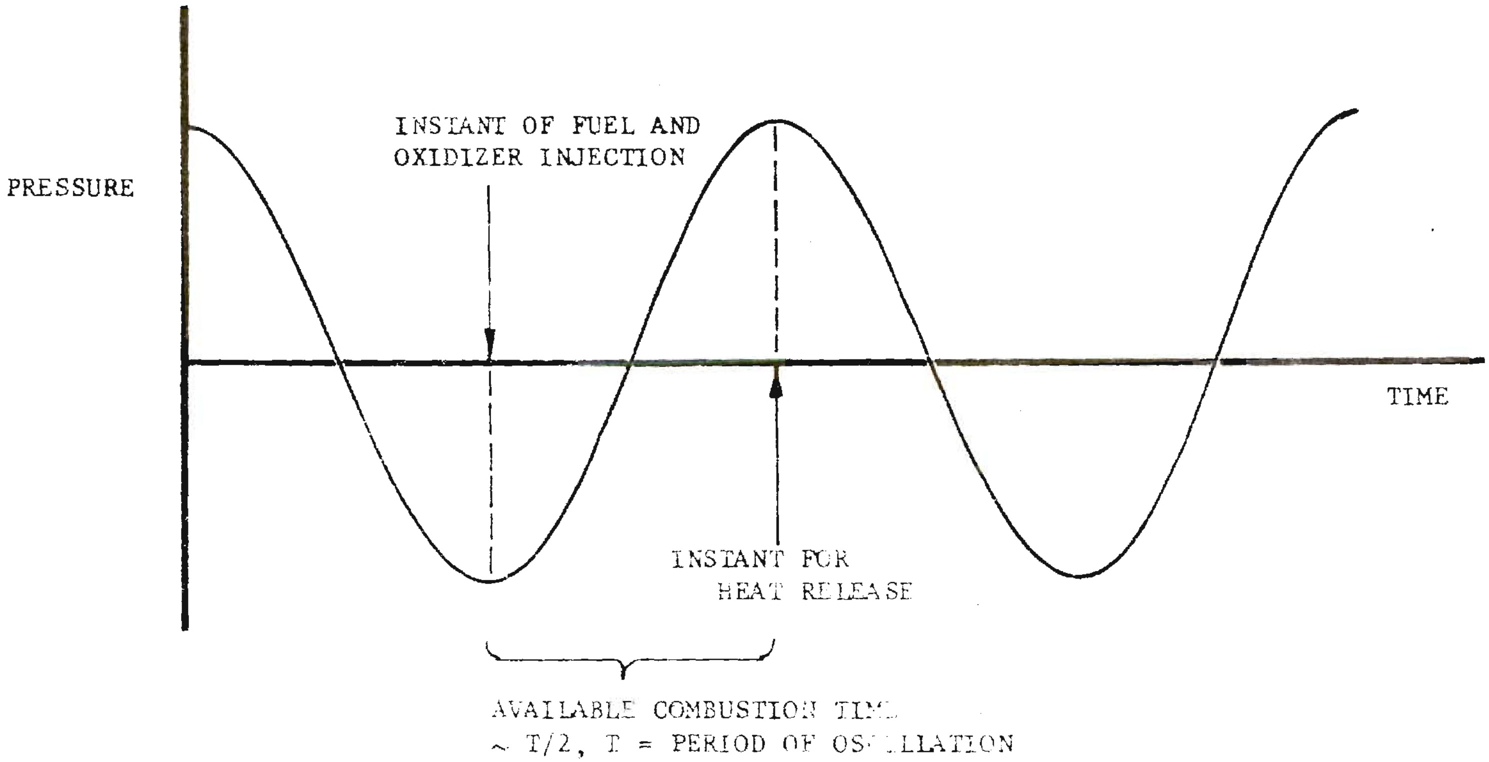


Figure 1. Qualitative Description of "Required" Combustion Time for Pulsating Combustion in a Schmidt Tube.

combustion time[6,7]. When the coal was not preheated, the developed combustors suffered from such problems as inability to stabilize the combustion process, incomplete combustion, and difficulties in maintaining pulsating combustion for different fuel/air ratios, and efforts to resolve these difficulties have resulted in cumbersome combustor design. Consideration of these problems at the initiation of this program had lead this group to the conclusion that burning coal in a Schmidt type pulsating combustor is bound to experience difficulties and the decision was made at the time to proceed with the development of a coal burning pulsating combustor that would be based upon the radically different Rijke tube oscillator[12]. As is described in the next section, results obtained to date under this program indeed demonstrate that the Rijke-like combustor developed by this group is capable of successfully burning coal and other solid fuels under a pulsating mode of combustion over wide ranges of operating conditions.

Next, before proceeding with the discussion of the characteristics of the pulsating combustor that was developed under this program, it would be appropriate to provide evidence in justification of claimed advantages of the pulsating combustion process, as listed under items (1) through (7) earlier in this section.

1. Highly Intense Combustion Process. In Schmidt type pulsating combustors and in the one developed under this program the occurrence of pulsating combustion is associated with the presence of acoustic velocity oscillations in the combustor in addition to a steady flow velocity component. The acoustic velocity component changes directions at a rate

that equals the frequency of pulsations and it is believed to greatly enhance the rate of mixing of fuel and oxidizer in the combustor, resulting in a high rate of combustion.

Additional explanation that has been advanced in the literature[1] for the high combustion rates of coal particles in pulsating combustors is the periodic stripping of the blanket of combustion products that surrounds the coal particle by the oscillating acoustic velocity. This action reduces the gas phase resistance (that is provided by the blanket of combustion products) to the migration of oxygen molecules toward the coal particle surface, resulting in the acceleration of the coal particle combustion. The above argument was based upon the notion that a coal particle is surrounded by a layer of combustion products after the initial phase of volatiles combustion. Recent combustion studies at Sandia[13] seem to indicate, however, that the particle and the blanket of combustion products tend to "separate" before the coal particle is completely burned even in the absence of pulsations. While this may appear to contradict the argument advanced in this paragraph, it is nevertheless plausible that the presence of pulsations enhances the stripping of the combustion products layers from the coal particles.

While there may be some questions regarding the exact mechanism(s) responsible for the high rate of coal burning due to pulsations, evidence provided by Sommers[8] and Lyman[9] who studied pulverized coal combustion clearly supports this claim. Finally, as will be discussed in the next section, our own work to date in this area indicates that the pulsating combustion process is characterized by a very high combustion rate per unit area (i.e.,

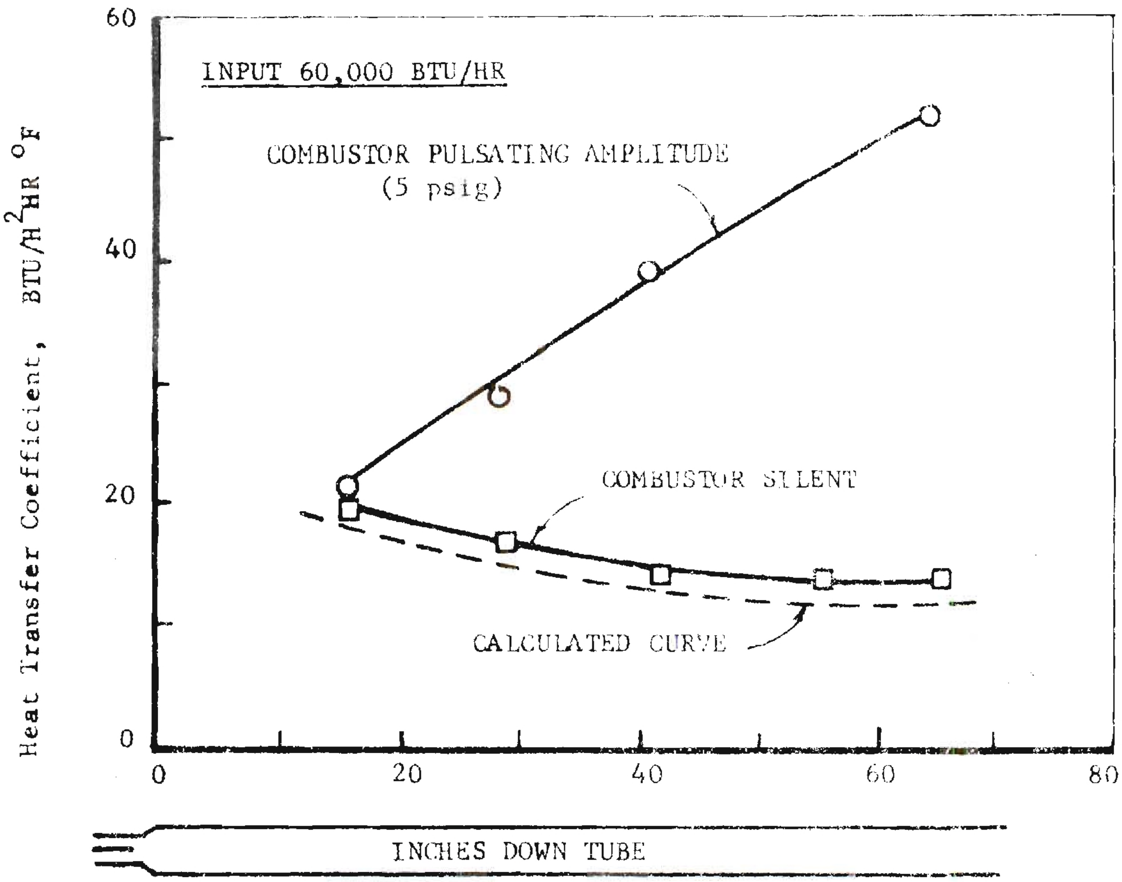


Figure 2. The Effect of Oscillations on the Distribution of Heat Transfer Coefficient in the Combustor.

Btu/ft^2hr).

The implication of a high combustion rate is that the resulting combustor will be smaller in size requiring a smaller initial capital investment.

2. Improved Heat Transfer Characteristics. The presence of acoustic oscillations is apparently responsible for considerably increased convective heat transfer from the flow to the surrounding boundaries. This phenomenon is well known and it had been responsible in the past for the melting of the walls of liquid propellant rocket motors after the onset of combustion instability. A good discussion of this phenomenon is provided by Hanby[14] and the resulting improvement in the convective heat transfer coefficient is described in Fig. 2 that was taken from Ref. 14. Figure 2 shows that the heat transfer coefficient depends upon the local flow conditions and that it reaches a maximum at a location of maximum acoustic velocity amplitude near the exit of the combustor. Comparing the plots provided in Fig. 2 for the heat transfer coefficients under pulsating and nonpulsating conditions clearly indicates the improved heat transfer processes that are associated with pulsating operation.

In practical terms, the improved heat transfer that is associated with the presence of acoustic velocity oscillations indicates that a given amount of heat can be transferred over a smaller heat transfer area, implying the need for a smaller heat exchanger and a smaller initial capital investment.

3. Reduced Pollutants Formation. This claim is supported by related studies conducted in the U. S. and the U. S. S. R. with pulsating combustors that utilized gaseous and liquid fuels. Reference 15 describes a Russian

investigation that specifically dealt with this problem. In this study, pollutants formation in two different combustor designs were compared under pulsating and nonpulsating (i.e., turbulent) operating conditions utilizing gaseous and liquid fuels. In all of the investigated cases, the results show reductions in the production of nitrogen oxides, carbon monoxide, hydrocarbons, sulfur dioxide and soot as a result of transition from nonpulsating to pulsating operation, with the reductions being significant (i.e., orders of magnitude) in most cases. In this case, the reduction in the production of carbon monoxide, hydrocarbons and soot also indicates that the presence of pulsations results in a more complete combustion process (i.e., higher combustion efficiency) which also supports some of the arguments advanced under item (1) above. Another point that needs to be emphasized is that pollutants reductions were observed while burning both gaseous and liquid fuels, suggesting that similar benefits might also occur during pulsating combustion of solid fuels.

Additional support for reduced nitrogen oxides formation during pulsating combustion is provided in the work of Belles[2] that deals with pulsating combustion of gaseous fuels. The following is a quote from Ref. 2 that describes these results: "Fortunately, our measurements show that the NO_x emissions of pulse burners are considerably lower than those of conventional furnaces, both in absolute concentration and also in terms of mass emitted per unit of usable heat appear to be real and they are most encouraging".

While the above observations need to be further investigated, especially for coal combustion, they nevertheless indicate that the use of pulsating combustion may reduce the production of pollutants to levels that will eliminate the need for complex combustor designs (e.g., combustion staging; see Ref. 16) and/or the incorporation of some expensive pollutants removal procedures or equipment into the system, resulting in reductions in both operational and/or capital investment costs.

4. Ability to Burn Unpulverized Coal. This is a characteristic of the Rijke-type pulsating combustor developed under this program and it is discussed in more detail in the next section. It's availability eliminates the need for investing in the acquisition of pulverizers and the continuous pulverizing cost, thus reducing both capital investment and operational costs. This feature should be particularly attractive to industries that are considering a switch to coal utilization and are considering the cost of such a move.

5. Self Aspiration. This feature implies that the combustor can "pump" its own oxidizer eliminating the need for auxiliary fans and/or pumps that are utilized in conventional combustors for moving the oxidizer (i.e., air) through the combustor. This unique feature of pulsating combustors offers the possibility of eliminating the costs associated with the purchase and operation of the needed air pumping equipment.

Before leaving this section, it should be pointed out that pulsating combustors can be operated under both self aspirating and forced oxidizer flow conditions.

6. Reduced Slagging and Keeping that Heat Transfer Surfaces Clean. The acoustic velocity oscillations that are associated with the pulsating combustion process result in back-and-forth motions (of different

amplitudes) of the gases along the various combustor and heat transfer surfaces. According to the Russian literature[5,16] and physical intuition, this motion results in a scrubbing type action on the surface that reduces or prevents slagging and foreign material depositions along these surfaces. This scrubbing action of the acoustic velocity in pulsating combustors may provide an acceptable solution to this serious problem.

7. <u>Ability to Burn with Little Excess Air</u>. Conventional combustors operate with air/fuel mixtures that may contain up to forty percent more air than is required for stoichiometric combustion. The use of excess air results in a decrease in the thermal efficiency of the system due to the costs associated with the thermal losses in the exhaust products, the pumping the additional air and the energy lost in vaporizing the moisture content of the air. In addition, the excess air results in lower temperatures of the combustion products which may adversely affect heat transfer processes. Thus, it is desired to operate with as little excess air as possible. In studies conducted by this group and those described in Ref. 15 it has been found that maximum amplitude of pulsating combustors might be able to operate efficiently with little excess air, resulting in combustors having higher thermal efficiencies.

The above discussion describes the observed advantages of the pulsating combustion process that provided the impetus for this research program. It consisted of the development of the Rijke-like, coal burning, pulsating combustor and its testing under different operating conditions. The results of these efforts are described in the following section.

PROGRAM ACHIEVEMENTS

This section is divided into two parts with the first part providing the background for the Rijke tube combustor that has been utilized in this study and the second part briefly describing achievements under this program.

The Developed Rijke Type Combustor

One of the initial objectives of this program was the development of a coal burning pulsating combustor that would not suffer from the shortcomings of the earlier designs, as discussed in the Introduction Section. Considerations of the problems that needed to be resolved and a personal communication with Severyanin during a 1978 visit to the Soviet Union lead to the conclusion that a pulsating combustor based upon the Rijke Tube[12] principles may offer an attractive alternative to the previously used Schmidt tube-like combustor designs[6].

The Rijke Tube, which was first developed in the 19th century, is shown schematically together with its associated acoustic wave structure in Fig. 3. In this configuration, the metal gauze is heated either apriori by a flame or concurrently by an electric current. In either case the wire acts as a heat source that induces an upward steady flow in the tube due to natural draft and periodic heating of the gas that results in the excitation of the natural mode of the tube, whose structure is also shown in Fig. 3. Theoretical investigations of the operation of the Rijke tube have been conducted by Carrier[17] and Culick[18]. In both cases it has been argued that the normalized heat transfer perturbation $Q'/\bar{Q}$ is related to the

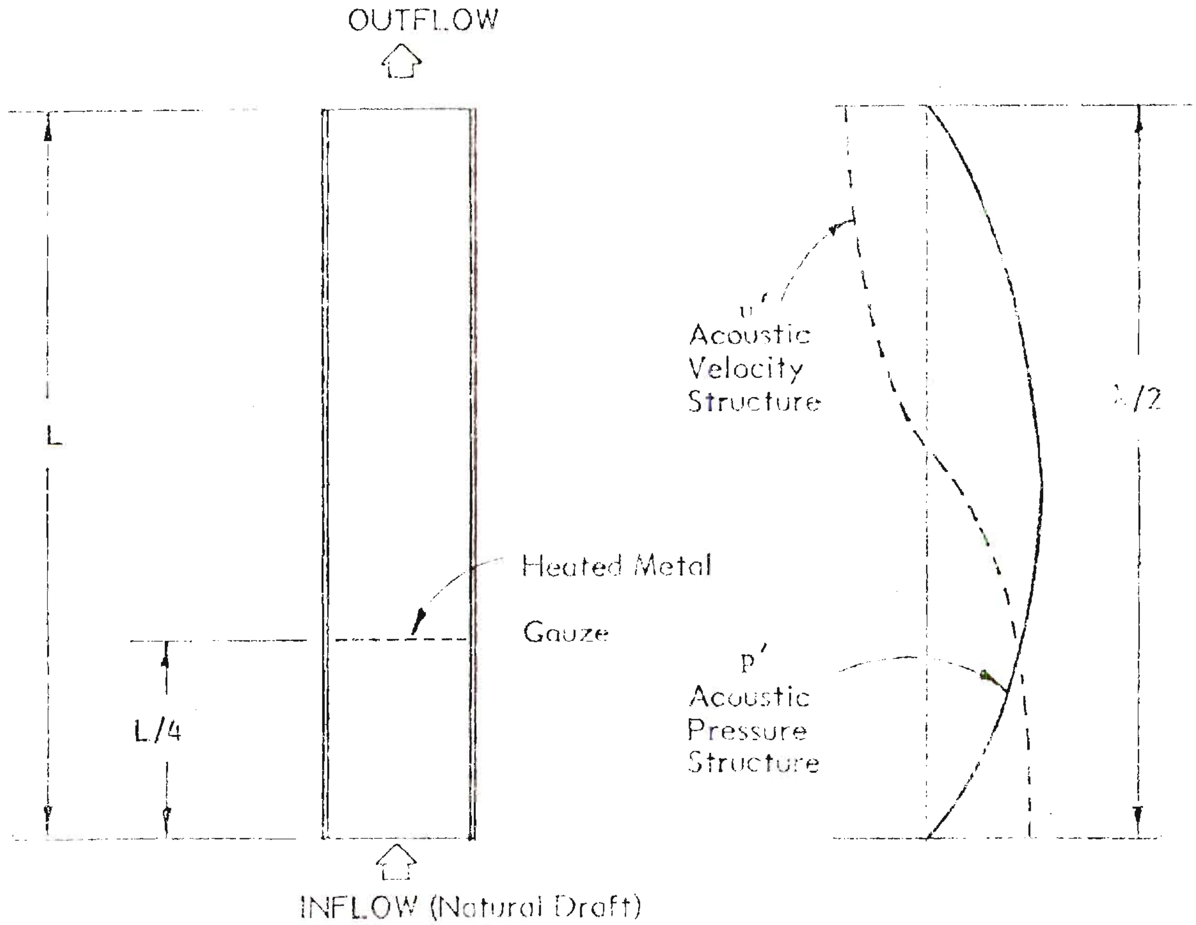


Figure 3. Schematic of the Rijke Tube

normalized velocity oscillation ($u'/\bar{a}$) via the relationship

$$Q'/\bar{Q} = qe^{-i\Psi} (u'/\bar{a}) \tag{2}$$

where Q is the heat transfer, q is a proportionality constant, Ψ is the phase difference between the heat addition and velocity perturbation and a the velocity of sound. The magnitude of the phase Ψ is of interest to the understanding of the physics of the problem. According to Ref. 17, $\Psi = 3\pi/8$ while according to Ref. 18 $0 \leq \Psi \leq \pi$.

Another point that needs to be emphasized is the importance of having a steady flow past the wire to the onset of an oscillation of the fundamental mode[18]. In the absence of such a flow, the frequency of any excited oscillation will be twice the frequency of the fundamental mode due to the fact that the heat transfer from the wire is proportional to the magnitude of the velocity and not its direction. On the other hand it can be shown that the presence of both a mean velocity and an oscillating velocity component may result in the excitation of the fundamental mode of the tube.

Additional experiments that influenced the present program were those conducted by Bosscha and Riess[10] in which hot flow was introduced into the bottom of a vertical tube and heat was removed from the flow at a distance 3L/4 from the bottom of the tube as shown in Fig. 4. As in Rijke's experiments, the removal of the heat at the indicated location resulted in the excitation of the fundamental mode of the tube as shown in Fig. 4. While it will not be done here, it should be pointed out that the Bosscha and

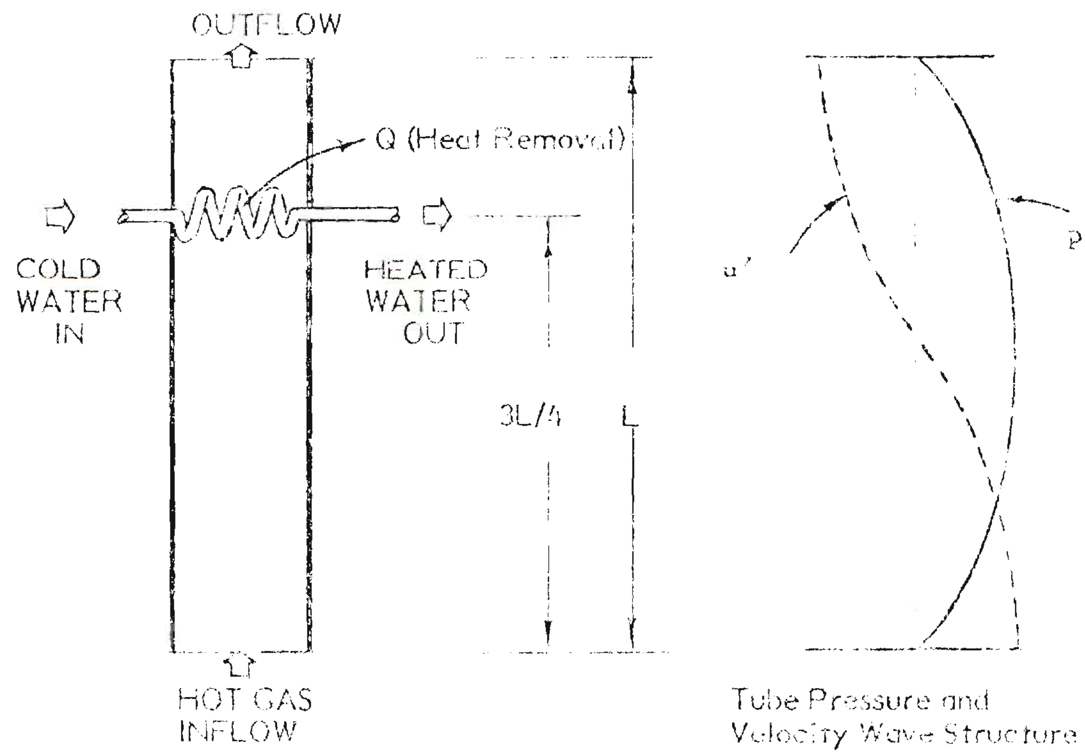


Figure 4. A Schematic of the Bosscha and Riess Experiments.

Riess experiments can be explained utilizing arguments similar to those used to explain the mechanisms responsible for the onset of the oscillation in the Rijke tube.

In summary, the Rijke, Bosscha and Riess experiments showed that the fundamental mode of a tube opened at both ends may be excited if heat is added at a distance of L/4 and/or removed at a distance of 3L/4 from the entrance of the tube. Keeping this in mind, a pulsating combustor could be designed by replacing the hot metal gauze by a coal burning bed at the L/4 position. While having a heat source at the L/4 position would be sufficient for obtaining a pulsating combustor, the pulsations would be amplified according to the Bosscha and Reiss experiments if heat is also removed from the hot combustion products at the 3L/4 position.

Summary of Accomplishments to Date

This section briefly summarizes the major accomplishments of this program to date. The objectives of this study were to (1) determine whether a coal burning pulsating combustor based upon the Rijke tube principles could be developed, and (2) determine the main operational characteristics of such combustor.

The developed Rijke tube pulsating combustor is shown in Fig. 5. It consists of cylindrical segments with internal diameter of 5.5" and wall thickness of 0.25". The total length is 108". Additional segments were built to permit variations in the combustor's length. Since the fuel remains in the bed over many cycles, this combustor does not suffer from the difficulties encountered in the previously discussed Schmidt type combustors in which

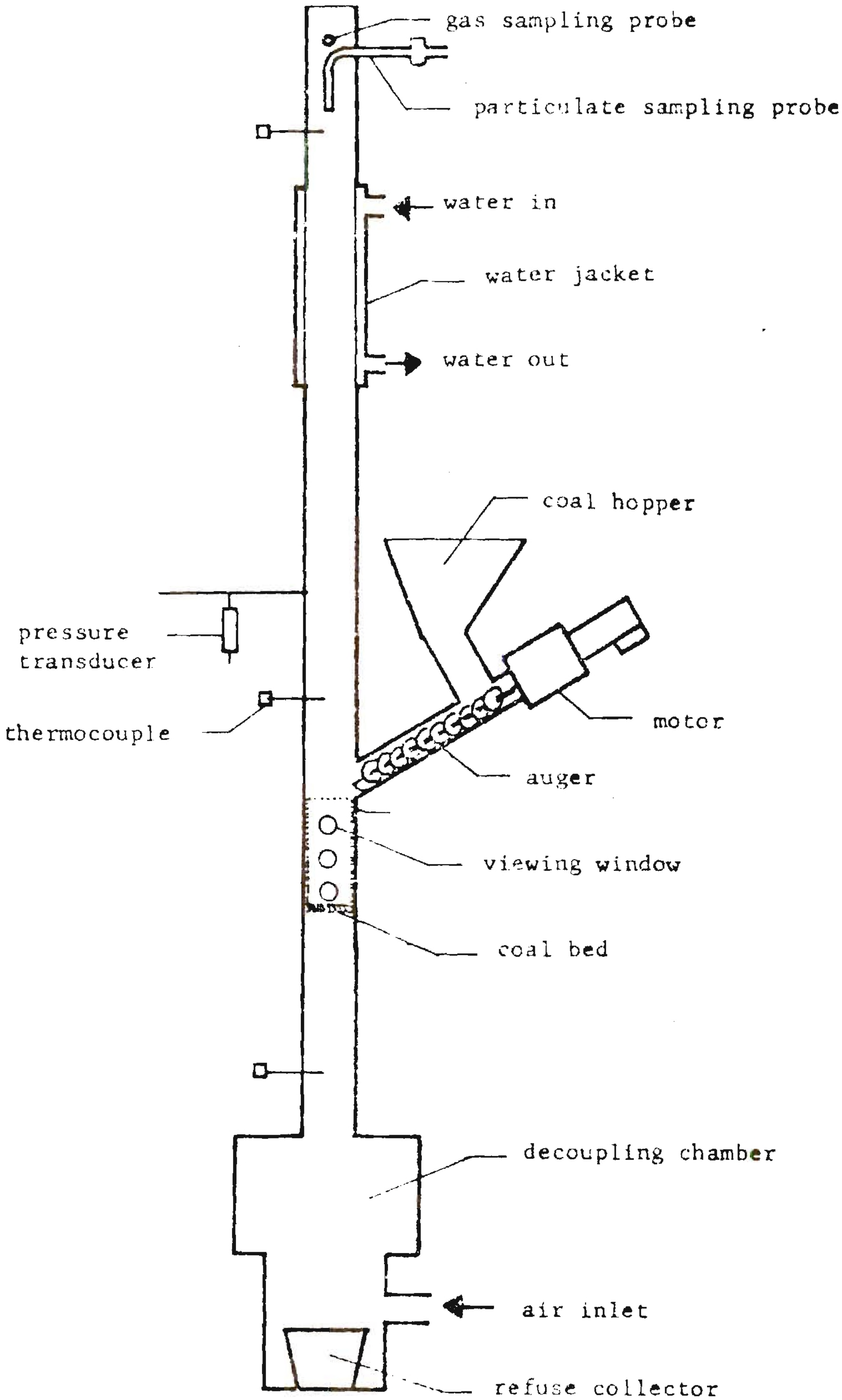


Figure 5. Schematic of the Developed Rijke Tube Pulsating Combustor.

preheating of the pulverized coal was required in order to satisfy the combustion time requirements. In this combustor configuration (see Fig. 5), coal is supplied to the combustion bed by means of a calibrated auger type feed system and pulsating combustion can be attained under either a self aspirating or a forced flow mode of operation. Under the forced flow mode, the decoupling chamber serves to guide the air into the combustor without altering the required open end boundary condition at the lower end. Coal was burned in a metal wire combustion bed located at L/4 and a water heating jacket was installed near the 3L/4 position. The lower decoupling chamber is disconnected from the tube when the combustor is operated under the self aspirating regime.

Developed measurement capabilities include thermocouple temperature measurements at different locations within the combustor, acoustic pressures using a condenser microphone, velocities using hot film, air flow rates during forced flow experiments using rotameters, high speed combustion zone photography utilizing specially designed viewing windows, coal feed rates utilizing a calibration curve of the auger type feed system, carbon monoxide and carbon dioxide gas concentrations at the exhaust flow using two Beckman model 864 infrared analyzers, and particulate emissions using a specially designed gas particulate sampling train. A sketch of the combined gas-particulate sampling train is shown in Fig. 6. The carbon monoxide and carbon dioxide gas concentration measurements in the exhaust flow provide data for the evaluation of the system's combustion efficiencies.

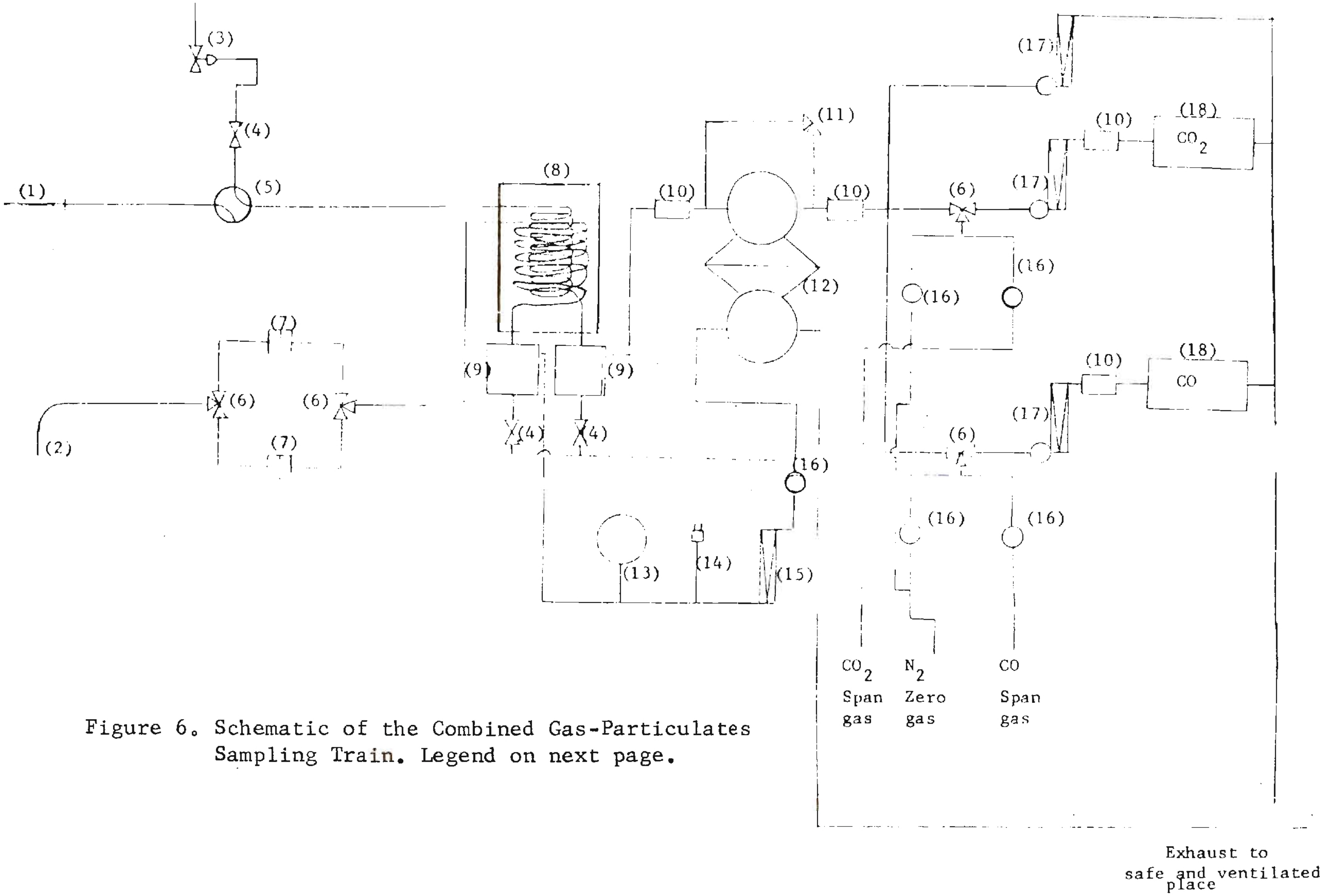


Figure 6. Schematic of the Combined Gas-Particulates Sampling Train. Legend on next page.

Legend (Fig.6)

(1) Cylindrical shape sintered metal filter (60) - gas sampling

(2) Nozzle type ½" diameter probe - isokinetic particulate sampling

(3) Pressure regulator with valve - purge system

(4) Two way valves

(5) Four way valve

(6) Three way valves

(7) Filter - retention of 99.7% of particles greater than 0.3

(8) Ice bath

(9) Separators

(10) Protection filters

(11) Relief valve

(12) Dual head pump

(13) Vacuum gauge

(14) Thermocouple

(15) Flowmeter

(16) Needle point valves

(17) Flowmeters with valve

(18) Infrared analyzers

In what follows, the major results obtained to date utilizing the above described experimental set up are briefly discussed.

1. Combustor Operation. This program has established that a Rijke type pulsating combustor can be utilized to burn coal and other solid fuels stably and continuously under either self aspirating or forced flow conditions. Pulsating combustion operation has been obtained consistently with the developed combustor within minutes after the ignition of the combustion bed.

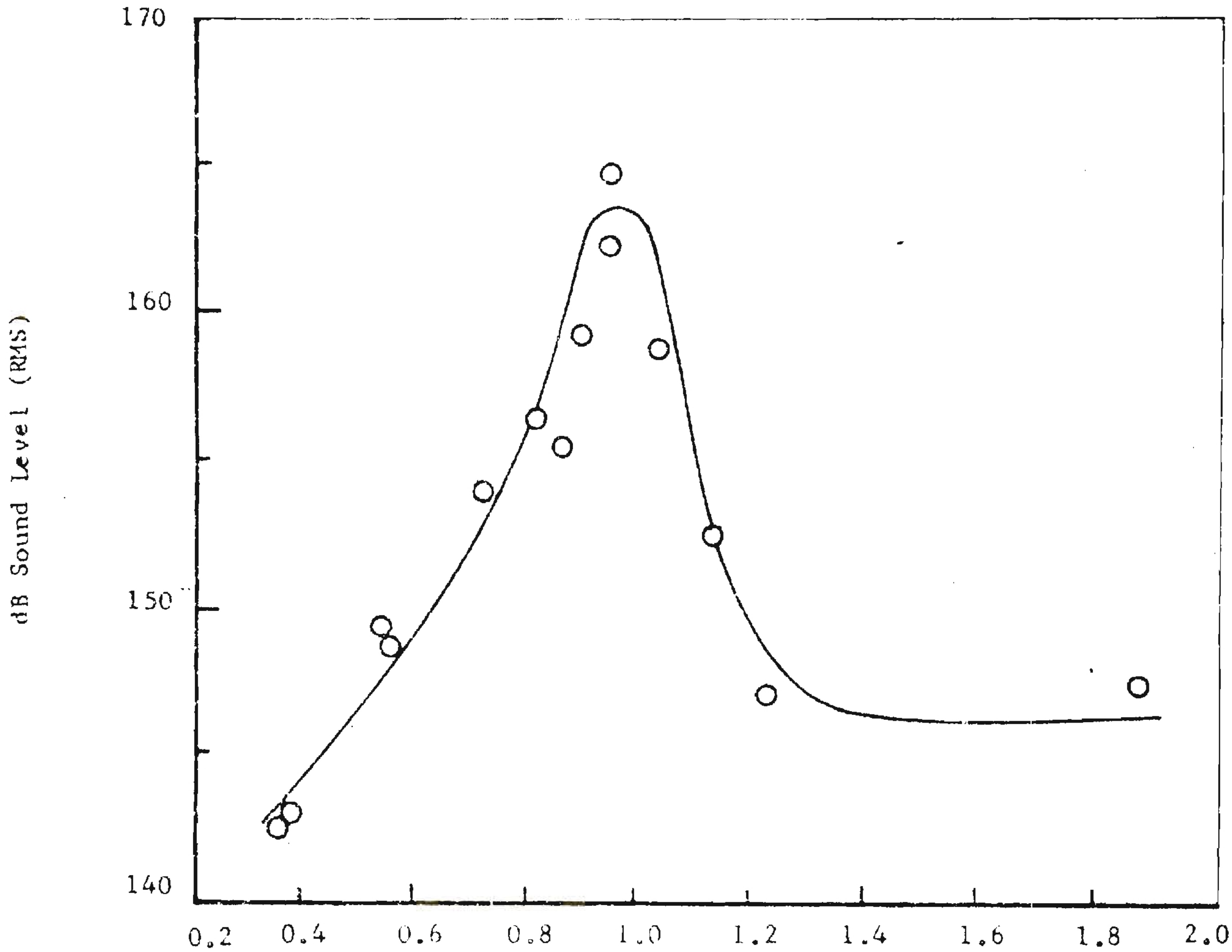
Utilizing a nine foot length combustor, results obtained to date showed that the frequency of pulsation was in the range 74 to 84 Hertz and that the pressure amplitude varied between 140 and 160 dB for operations under the self aspirating mode and between 150 and 165 dB for operations under the forced flow mode.

2. Characteristics of the Developed Pulsating Combustor. One measure of the performance of the developed combustor is the amplitude of the excited acoustic oscillation. In this case an increase in the amplitude implies better coupling between the combustion process and the natural acoustic mode of the combustor that should result in "better" mixing and consequently more efficient combustion process. In addition, the increase in amplitude may result in better heat transfer processes and reduced pollutants formation. Thus, measured dependence of the amplitude of the oscillation upon different combustor operating parameters has been used as an indication of the performance of the system with a higher amplitude operation implying a more "efficient" operation.

Tests conducted to date showed that the amplitude of pulsations depends upon the location of the combustion zone within the lower half of the tube. For a given combustion bed configuration the amplitude is near maximum when the bed is located a distance of L/4 from the entrance to the tube. Also, moving the bed to different positions results in the excitation of higher harmonics of the fundamental combustor mode.

The amplitude also depends upon the degree of accumulation of coal in the bed. For low or zero accumulation, acoustic energy dissipation in the bed is minimized and the amplitude of the combustor pulsations increases.The amplitude of the oscillation decreased as the length of the combustor was decreased. As a matter of fact maximum amplitude was obtained with the maximum tested combustor length of 9 feet. This result indicates that the various processes responsible for wave excitation and wave losses are frequency dependent and that there is an optimum frequency of operation for Rijke Tube Combustors. It appears that for the present combustor a further (small) increase in length may result in further amplitude increase. These results also indicate that an investigation of the optimum frequency of operation is desirable.

3. Forced Flow Operation. Pulsating operation under forced flow conditions permitted testing under a variety of air/fuel ratios. A series of tests were conducted with coal and wood for different air/fuel ratios and the results, plotted in Figs. 7 and 8, show that the amplitude of the oscillation strongly depends upon the air/fuel ratio with the maximum occurring near stoichiometric operation. These results are consistent with previous Russian



$$\alpha = \frac{(m_{Air}/m_{Fuel})_{Exp}}{(m_{Air}/m_{Fuel})_{Stoich}}$$

Figure 7. Measured Acoustic Pressure Amplitudes for Experiments Conducted with Coal Burned under Different Air/Fuel Ratio and Nominal Coal Feed Rate of 50 gr/min.

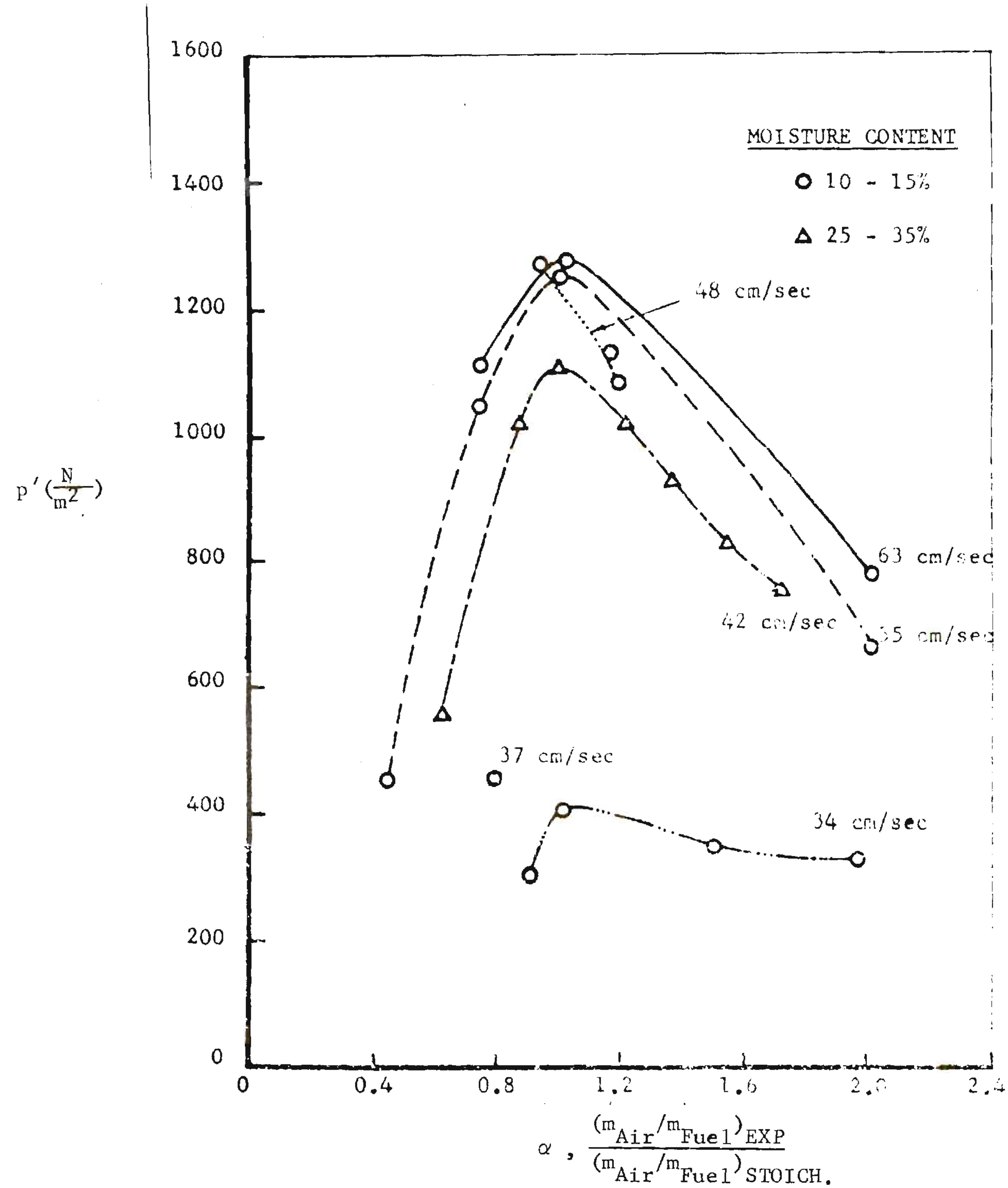


Figure 8. Measured Acoustic Pressure Amplitudes for for Experiments Conducted with Wood Burned under Different Air/Fuel Ratios and Different Steady Velocities.

results[15] and it supports the previous claim that the pulsating combustors could be operated with little excess air, resulting in higher thermal efficiencies for the combustor.

Figure 8 also indicates that the amplitude of the oscillation depends upon the magnitude of the steady state velocity $\bar{u}$, with the available data showing that an increase in $\bar{u}$ leads to an increase in the amplitude of pulsation. These data indicate that the coupling (i.e., driving) between the combustion process and the oscillation strongly depends upon the magnitude of the steady velocity through the combustion zone. This result also indicates that this coupling process needs to be further investigated and that forced flow operation which provides an independent control of the magnitude of $\bar{u}$ may be preferable in terms of providing means for controlling the operation of the pulsating combustor.

4. <u>Fuel Rich Operation</u>. Another significant aspect of the data presented in Figs 7 and 8 is the demonstration that pulsating combustion operation was achieved under fuel rich conditions (i.e., $\alpha < 1$). Since for $\alpha < 1$ the exhaust flow is fuel rich and it could possibly be used as a fuel, then these results suggest that the developed pulsating combustor, or a modified version, could be possibly used in solid fuel gasification applications.

5. <u>Comparisons Beween Pulsating and Nonpulsating Operation</u>. During the course of this study, it has been found that opening one or two small holes in the wall of the combustor tube a few inches above the combustion bed results in the cessation of the pulsations. This capability allowed for qualitative comparisons of the characteristics of the combustion zones and exhaust flows under pulsating and nonpulsating conditions. When the

combustor was pulsating, visual observations indicated that the luminous combustion zone was short exhibiting extremely intense "agitation" of the gases within the combustion zone. In addition, flamelets moving periodically downward (against the direction of the steady upward flow) through the holes of the wire mesh supporting the coal bed were observed. This downward motion was undoubtedly caused by the back-and-forth motion of the acoustic velocity near the combustion bed which is also responsible for intensified mixing within the combustion zone; the latter is probably responsible for the "compactness" of the observed combustion zone. In addition, the exhaust flow leaving the combustor appeared clear and smoke free.

When pulsations are absent, the combustion bed with the through air flow probably approximates the combustion in an stoker type combustor. In this case, observations of the fuel bed showed the presence of a relatively long luminuous combustion zone that "started" someplace near the middle of the bed and extended some distance above the bed. Furthermore, the combustion zone lacked the "intensity" or "vibrations" observed during pulsating combustion and there were no flamelets protruding below the wire mesh coal support. Finally, the presence of black smoke was clearly visible in the exhaust flow.

Also, comparisons of exhaust flows concentrations showed that the presence of pulsations reduces CO and concentrations while increasing CO_2 concentration, implying that pulsations result in a more complete combustion process.

The observed differences in the characteristics of the combustion zones and exhaust flows between the two modes of combustion strongly support the argument that the presence of acoustic velocity oscillations near the combustion bed during pulsations is responsible for intensified mixing and, consequently, more rapid and complete burning of the solid fuel in the bed.

6. Multiple Fuel Operations. To date, pulsating operation was studied under this program utilizing different commercially available coals (one of which was supplied by Georgia Power) and a variety of woods containing different amounts of moisture. While the amplitude of the resulting pulsation depended upon the characteristics of the fuel, pulsating operation was obtained in all instances. As a matter of fact, the combustor had no problems burning wood with forty percent moisture content and freshly cut wood, which cannot be readily burned in most combustors.

These observations together with earlier[19] successful operation of a Rijke tube combustor with a gaseous fuel suggest that Rijke type, pulsating combustors capable of multiple fuels operation, including low grade fuels (e.g., freshly cut wood), could be designed in the future.

7. Combustion Efficiencies. The carbon dioxide and carbon monoxide concentration measurements in the exhaust flow together with the measured air/fuel ratios, the determined coal composition (i.e., by ultimate analysis); and considerations of mass conservation were used to evaluate the combustions efficiencies of the system under different conditions in the forced flow mode of operation. For a coal feed rate of 50 gr/min and different air/fuel ratios, the combustion efficiency ranged from 89 to 98.5%

for values of α (i.e., the normalized air/fuel ratio) ranging from 1.03 to 1.22, respectively. The combustion efficiencies for corresponding non pulsating operations were always found to be lower (e.g., in some instances 15% lower) than the values determined for pulsating operation.

8. Combustion Intensities. Using the computed combustion efficiencies and measured coal feed rates the combustion process heat release rates were calculated. Maximum heat release rates of 750,000 Btu/hr ft^2 were achieved with stoichiometric operations, a value that compares very favorably with energy release rates of recent state of the art combustors[20].

9. Particulate Emission. A plot showing the relative amounts of particulates generated under different air/fuel ratios and nominal feed rate of 50 gr/min is presented in Fig. 9. A drastic reduction in particulates formation with an increase in α is observed with the particulates formation reaching an almost constant minimum level for α larger than 1.1. One should also note that for all of the tested α's, particulates formation was considerably higher under non pulsating operation.

Report Summary

The results obtained under this research program demonstrated that unpulverized coal can be burned continuously and stably in a Rijke type combustor. Under pulsating operation, the presence of acoustic oscillations enhances the mixing between oxidizer and fuel which increases the efficiency and heat release rate of the combustor. Maximum amplitudes occur when the air/fuel ratio is nearly stoichiometric which suggests that

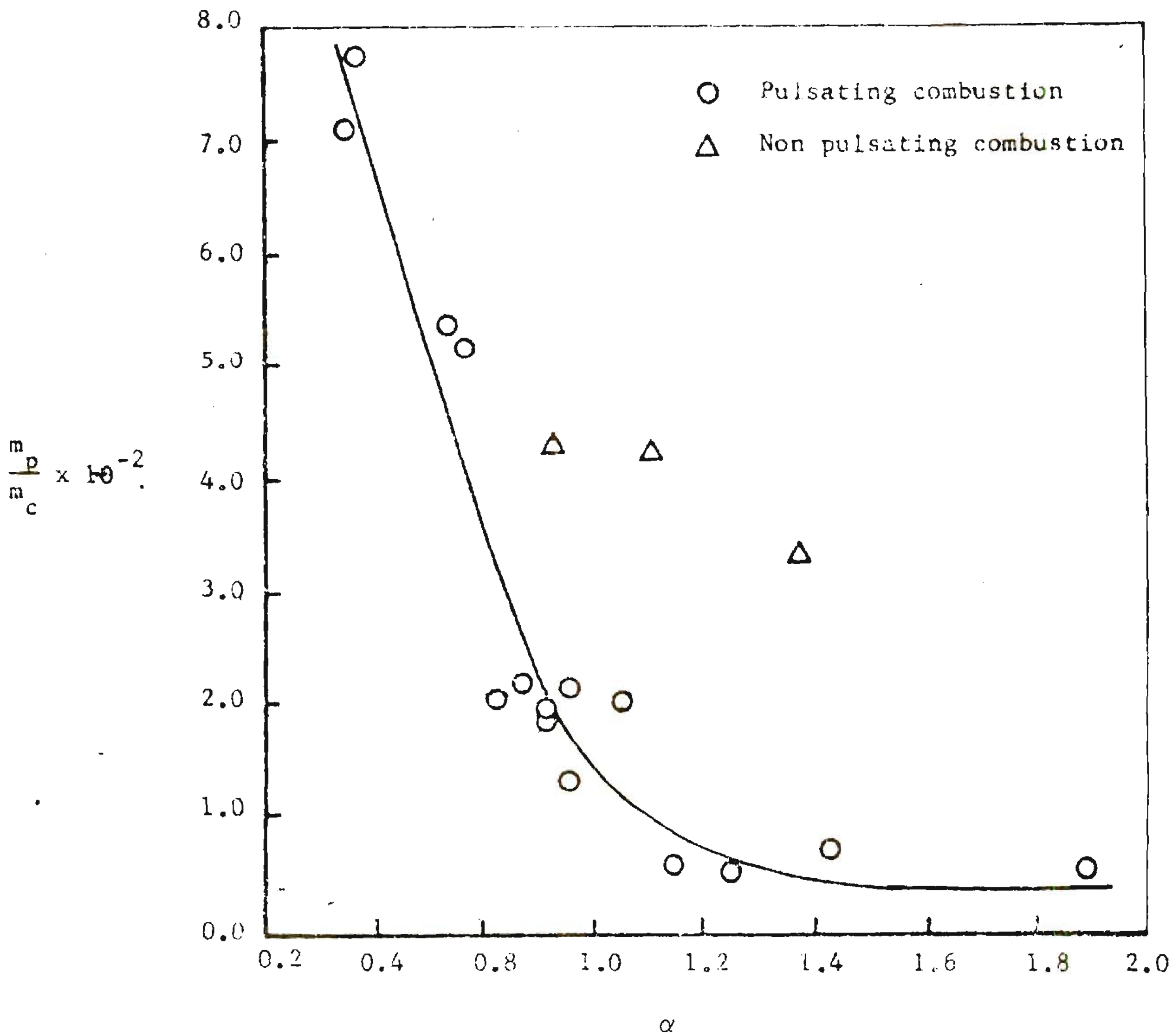


Figure 9. Dependence of the Particulate Generation upon the Air/Fuel Ratio for Nominal Feed Rates of 50 gr/min (m_p/m_c = ratio between collected mass of particulates and feed rate of the coal).

devices (e.g. boilers, water heaters, etc.) utilizing such a pulsating combustor should possess high thermal efficiencies. It was also verified that pulsating combustion operation of the developed combustor is possible for a variety of air/fuel ratios, including very fuel rich conditions (eg. = 0.36). Under these fuel rich situations, the exhaust flow is combustible indicating that the developed Rijke combustor could possibly be also utilized as a coal gasifier. In closing, the results obtained under this program to date demonstrate that with further development, Rijke type pulsating combustors may provide energy users with an attractive means for deriving energy from coal.

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